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LEARNING GENETICS AND EVOLUTION THROUGH SCIENTIFIC PRACTICES. A CASE STUDY WITH SECONDARY STUDENTS

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ESCUELA DE DOUTORAMENTO INTERNACIONAL

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Learning genetics and evolution through scientific practices. A case study with secondary students

Dna. Noa Ageitos Prego

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Learning Genetics and Evolution through scientific practices. A case study with secondary students

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PRESENTATION

This thesis is structured following the guidelines and regulations established for the publication of theses as a compendium of research articles. This was approved by the resolution *12 de julio de 2017 por la que se publica el Reglamento de estudios de doctorado* by means of which the Regulation on PhD studies was published, and which was approved in the Pleno ordinario del Consejo de Gobierno de 12 de junio de 2017, regulated by the Real Decreto 99/201.

In accordance with the regulations governing the format for the presentation of theses as a compendium of publications, we have structured the thesis in the following manner:

Section 1: Introduction
Section 2: Publications
Section 3: Discussion
Section 4: Conclusions and educational implications
Section 5: References

This thesis contains three original articles framed within the same line of research; the study of scientific and reasoning practices by secondary school students when learning genetics and evolution. The three articles are presented in the original language and format in which they were originally published. In addition, a fourth article is included, since it presents the design of the teaching sequence that involves the tasks object of analysis in this thesis.

1. Puig, B., Ageitos, N. & Jiménez-Aleixandre, M. P. (2017). Learning Gene Expression Through Modelling and Argumentation. A Case Study Exploring the Connections Between the Worlds of

Knowledge. *Science & Education*, 26 (10), 1193-1222. https://doi.org/10.1007/s11191-017-9943-x.

2. Ageitos, N. & Puig, B. (2019). Argumentation as a tool to explain the evolutionary links between human diseases: a case study. *Journal of Biological Education*. https://doi.org/10.1080/00219266.2019.1667409.

3. Ageitos, N., Puig, B. & Colucci-Gray, L. (in press). Examining reasoning practices and epistemic actions to explore students' understanding of genetics and evolution. *Science & Education*. DOI: 10.1007/s11191-019-00086-6

4. Ageitos, N.; Puig, B. y Calvo-Peña, X. (2017). Trabajar genética y enfermedades en secundaria integrando la modelización y argumentación científica. *Revista Eureka sobre Enseñanza y Divulgación de las Ciencias*, 14 (1), 86-97. DOI: https://doi.org/10.25267/Rev_Eureka_ensen_divulg_cienc.2017.v14.i1.07.

CONTENTS

RESUMO

O obxectivo principal da tese é examinar as prácticas científicas e de razoamento, así como as accións epistémicas levadas a cabo polo alumnado de secundaria durante a aprendizaxe de xenética e evolución no contexto de explicar diversas enfermidades humanas. Para abordar este obxectivo explóranse, por unha banda, a participación do alumnado nas prácticas de modelización e argumentación e as súas interaccións en relación cos mundos do coñecemento; e por outra banda, a retórica e a argumentación, así como e accións epistémicas que mobiliza o alumnado no discurso oral.

O obxectivo xeral da tese concrétase nestes tres obxectivos específicos e as súas respectivas preguntas de investigación:

O1. Examinar as interaccións entre a modelización e a argumentación e as súas conexións cos tres mundos do coñecemento no contexto de aprendizaxe da expresión dos xenes en alumnado de secundaria. Isto abórdase a través das seguintes preguntas de investigación, analizadas no artigo 1:

P1) Que operacións de argumentación e modelización realizan os estudantes no proceso de modelizar a expresión dos xenes? E especificamente, que operacións permiten conectar os tres mundos do coñecemento?

P2) Cales son as interaccións entre a modelización e a argumentación no proceso de modelizar a expresión dos xenes? En que medida estas interaccións axudan a conectar os tres mundos do coñecemento e modelizar a expresión dos xenes?

O2. Examinar os argumentos e datos empregados polo alumnado de secundaria para explicar as relacións entre dúas enfermidades

humanas na aprendizaxe de xenética e evolución. Este obxectivo abórdase a través das seguintes preguntas de investigación, analizadas no artigo 2:

P3) Cal é a natureza dos argumentos escritos do alumnado para explicar as relacións evolutivas entre dúas enfermidades humanas?

P4) Que datos mobilizan os estudantes e como os utilizan para apoiar os seus argumentos sobre as relacións entre estas dúas enfermidades?

O3. Examinar as interseccións entre a retórica e a argumentación, e as accións epistémicas que mobilizan os estudantes na comprensión de xenética e evolución en alumnado de secundaria. Este obxectivo abórdase a través das seguintes preguntas de investigación, analizadas no artigo 3:

P5) Que marcos de pensamento emerxen da análise da retórica e argumentación na aprendizaxe de xenética e evolución polo alumnado?

P6) Que accións epistémicas axudan ao alumnado a establecer relacións explicativas entre xenética e evolución no contexto de relacionar dúas enfermidades?

Fundamentación teórica

O marco teórico desta investigación sitúase dentro da educación epistémica en ciencias (Barzilai e Chinn, 2018). Esta liña de pensamento ve a ciencia como un conxunto de prácticas que teñen unha natureza social e cultural propias da comunidade na que se desenvolven. Os aspectos máis relevantes da fundamentación teórica desta tese forman parte destes corpos de investigación: a) os mundos de coñecemento (Tiberghien, 2000), así como as interaccións entre a argumentación e a modelización nos procesos de modelización científica; b) a retórica e a argumentación e as súas interseccións no discurso; c) a aprendizaxe de xenética e evolución.

Os mundos de coñecemento e as interaccións entre prácticas científicas nos procesos de modelización

Existe consenso na comunidade científica á hora de considerar que para lograr a aprendizaxe de ciencias é preciso que o alumnado participe nos obxectivos epistémicos propios da ciencia (Kelly e Licona, 2017). Unha das propostas para acadar este obxectivo é situar a participación nas prácticas científicas no centro do ensino e aprendizaxe de ciencias (Jiménez-Aleixandre e Crujeiras, 2017). A *modelización* é unha práctica científica que se basea en explicar como ou por que algo funciona como funciona para entender mellor o mundo natural (Knuuttila, 2005).

Segundo Tiberghien (2000), a interpretación do mundo material por unha persoa ou unha comunidade é unha actividade de modelización. Para Tiberghien (2000) a modelización pon en marcha dous mundos de coñecemento, o mundo dos obxectos e eventos e o mundo das teorías. Esta investigación parte desta visión de modelización e modifícaa. O mundo dos obxectos e eventos refírese a aqueles aspectos que son observables e que podemos percibir. Mentres que o mundo das teorías está formado pola dimensión teórica e os modelos que se constrúen cando se estuda unha área do coñecemento.

Nesta tese realízase unha modificación do marco proposto por Tiberghien (2000), integrando as representacións externas como un terceiro dominio do coñecemento ou mundo do coñecemento, xunto cos mundos das "teorías" e dos "obxectos e eventos". Nesta perspectiva, os procesos de modelización poden ser vistos en termos de interaccións entre os tres mundos do coñecemento. Suxerimos que a participación do alumnado na aprendizaxe baseada en modelos pode contribuír ao desenvolvemento de operacións relacionadas coa argumentación e a modelización, así como ás súas interaccións.

Entendemos que o acto de modelizar é intrinsecamente argumentativo, xa que case todos os aspectos da modelización, dende a formulación do obxectivo ata a comunicación do modelo, como a revisión e avaliación do mesmo, están intimamente relacionados coa argumentación (e.g., Berland e Reiser, 2009; Passmore e Svoboda, 2012).

Existe un aumento de interese na investigación sobre prácticas científicas na análise conxunta das prácticas de argumentación e modelización (e.g., Clark, Sengupta, Brady, Martinez-Garza, e Killingsworth, 2015; Passmore e Svoboda, 2012). Esta tese pretende investigar que operacións teñen lugar no desempeño de ambas prácticas científicas e as súas posibles interaccións.

A retórica e argumentación e as súas interseccións no discurso

A argumentación pode ser incluída dentro das prácticas epistémicas e científicas, máis tamén dentro das prácticas de razoamento. Dentro destas, autores como Martins, Mortimer, Osborne, Tsatsarelis, e Jiménez-Aleixandre (2001) propoñen explorar un conxunto máis amplo de estratexias discursivas, alén da argumentación científica, como pode ser a retórica. Son escasas as investigacións que se centran en analizar a retórica na aprendizaxe de ciencias polo alumnado, a diferenza dos estudos que abordan a argumentación (Osborne, 2001). En consecuencia, pouco se coñece sobre o papel da retórica na construción de argumentos e na aplicación do coñecementos. En liña con Osborne (2001), esta tese propón a análise da retórica como vía para lograr unha mellor comprensión sobre como promover a argumentación científica en articulación coa aplicación do coñecemento na aula de ciencias.

Esta tese parte da visión de que a argumentación é unha práctica social na que os membros da comunidade procuran explicar os fenómenos estudados avaliando, criticando e revisando as conclusións a través do discurso (Berland e Reiser, 2011). Vemos a retórica como unha compoñente vital da linguaxe, así como unha ferramenta para comprender o discurso científico. O termo retórica pode ser empregado para referirse á articulación de diferentes modos de comunicación, como linguaxe, imaxes e xestos, para producir textos coherentes, que axudan a dar forma a unha visión determinada do mundo (Driver, Newton e Osborne, 2000). Os estudos sobre a linguaxe fixeron fincapé sobra as interseccións entre a argumentación e a retórica como prácticas discursivas que poden dar forma ao pensamento dos estudantes e a outras actividades epistémicas (Kelly e Bazerman, 2003).

Aprendizaxe de xenética e evolución. Principais dificultades

Durante as últimas décadas, producíronse grandes avances conceptuais e tecnolóxicos no campo da xenética, moitos dos cales chegan ao ámbito público. Todo isto require a comprensión de ideas científicas sobre xenética por parte da cidadanía (Feinstein, Allen e Jenkins, 2013; Ryder 2001). A alfabetización en xenética implica ser capaz de comprender, utilizar ou responder a información sobre fenómenos xenéticos e tecnoloxías que un individuo pode atopar en situacións da vida cotiá (Duncan, Rogat e Yarden, 2009). É dicir, tomar decisións informadas sobre cuestións sociais e científicas complexas (Shea e Duncan, 2015).

A xenética é unha disciplina que presenta dificultades á hora de ensinar e aprender. Knippels (2002) agrupa en cinco categorías as dificultades atopadas na aprendizaxe de xenética: 1) vocabulario e terminoloxía específica; 2) contido matemático nas tarefas de xenética mendeliana; 3) procesos citolóxicos; 4) natureza abstracta da xenética; 5) complexidade da xenética: os problemas macro-micro. Ademais, autores como Mills Shaw, Van Horne, Zhang e Boughman (2008), fan referencia a dificultades específicas relacionadas con: a) tecnoloxías xenéticas; b) determinismo xenético; c) patróns de herdanza; d) natureza dos xenes e do material xenético; e) base xenética das enfermidades; f) investigación en xenética; g) tecnoloxías reprodutivas.

En resposta a estas dificultades, xorden iniciativas docentes e propostas para superalas, sendo a unidade didáctica desta tese un exemplo que toma en conta no seu deseño aportes previos da literatura. En concreto, propostas orientadas a mellorar a comprensión do modelo de expresión dos xenes e as relacións fenotipo e xenotipo. En liña con Reinagel e Bray Speth (2016), proponse a modelización como unha práctica que axuda a mellorar a comprensión sobre a relación entre os xenes e os fenotipos.

A evolución é un dos conceptos fundamentais da bioloxía, mais a súa ensinanza e aprendizaxe presenta desafíos (Andrews et al., 2017). Existen numerosos estudos que amosan ideas alternativas sobre a teoría da evolución (Alberts e Labov 2004; Ferrari e Chi, 1998; Miller, Scott e Okamoto, 2006). De acordo a Alters e Nelson (2002) estas ideas poden clasificarse segundo a súa orixe en: a) ideas que xorden de experiencias cotiás; b) ideas construídas polo propio alumnado, nas que estes acomodan nova información ao seu marco anterior; c) ideas ensinadas informalmente por outras persoas ou aprendidas na ficción; d) ideas vernáculas, que xorden da diferenza entre a definición científica dunha palabra e o seu uso cotián; e) conceptos erróneos e relixiosos.

Existen escasas investigacións que aborden conxuntamente a aprendizaxe de xenética e evolución. Un dos traballos que toma como referencia esta tese é o de Kalinowski, Leonard e Andrews (2010), que mostra dificultades por parte do alumnado universitario para usar conceptos de xenética molecular á hora de construír explicacións de evolución. Isto contrasta coa idea de que a evolución para ser comprendida precisa de conceptos de paleontoloxía, embrioloxía, bioxeografía, bioloxía molecular e xenética de poboacións (Mayr, 2002). Isto leva a que cada vez exista maior consenso sobre a necesidade de potenciar os vínculos interdisciplinarios en todas estas áreas para promover a comprensión e aprendizaxe dos estudantes (Tibell e Harms, 2017).

Xenética e evolución articúlanse nesta tese no contexto de relacionar dúas doenzas humanas, unha delas con compoñente xenética.

Metodoloxía

Esta tese forma parte da investigación cualitativa, a cal intenta investigar como as persoas constrúen o mundo ao seu redor, que fan ou que lles ocorre, tratando de obter unha visión significativa e rica da observación da situación. En concreto, enmárcase dentro dos estudos de caso que se relacionan con fenómenos sociais e poñen o foco de atención nunha ou varias das súas manifestacións e no seu entorno (Swanborn, 2010). Esta tese aborda un *estudo de caso único* (Yin, 2003) de tipo exploratorio, no que se analizan os desempeños de prácticas científicas por un grupo de vinte estudantes en diversas tarefas que forman parte dunha unidade didáctica de xenética e evolución.

O contexto no que se desenvolve o estudo é un instituto de ensino secundario (IES) do interior de Galicia. O centro, malia situarse nunha vila, considérase semiurbano e recibe alumnado do centro da vila e de diversas aldeas que se atopan preto. O nivel socio-cultural é medio e gran parte do alumnado continúa os estudos de bacharelato ao rematar o Ensino Secundario Obrigatorio (ESO). A elección do centro participante estivo motivada polo interese do profesorado en participar no proxecto de investigación.

Os participantes son dúas aulas de 20 estudantes de entre 15 e 16 anos de 4º ESO e os seus dous profesores (T1 e T2) da materia de bioloxía e xeoloxía. As dúas aulas reuníronse e o alumnado traballou como un soa aula. Ambos docentes levaban máis de 10 anos no ensino público e varios anos ensinando neste mesmo centro. No caso de T1, cabe mencionar, que participou previamente nunha investigación de didáctica de ciencias centrada no desenvolvemento da modelización en xeoloxía. Ademais, este docente elabora os seus propios modelos para traballar con eles na aula.

Os dous profesores discutiron en previas reunións coas investigadoras a posta en práctica das tarefas, o deseño e adecuación destas, valorando a súa idoneidade tendo en conta as necesidades dos participantes. Estas reunións realizáronse tanto no centro educativo como no centro de traballo da investigadora. Cómpre sinalar que ambos docentes desenvolveron as tarefas na aula, mais o seu rol foi distinto. T1 dirixía as sesións e guiaba aos distintos grupos no desenvolvemento das actividades e T2 apoiaba a T1 no desenvolvemento das actividades Ambos docentes respondían as demandas dos distintos grupos e proporcionaban a andamiaxe que demandaba cada grupo.

As actividades obxecto de análise nesta tese forman parte dunha primeira secuencia didáctica sobre xenética e evolución e prácticas científicas. En concreto analízanse a primeira e última tarefas grupais. O deseño das actividades tivo en conta os contidos relacionados con xenética e evolución do currículo vixente (CCEOU, 2015), ademais dos resultados de investigacións anteriores sobre ensinanza de xenética e evolución. A secuencia aborda diversas doenzas con compoñente xenética que requiren a comprensión e aplicación do modelo de expresión dos xenes. Ademais, co fin de vencellar xenética e evolución, inclúese unha doenza que se relaciona evolutivamente cunha das enfermidades previamente traballadas.

A secuencia didáctica 1 inclúe catro actividades realizadas en pequenos grupos en seis sesións. As actividades ordénase seguindo dous criterios: 1) o nivel de complexidade das enfermidades, desde unha enfermidade máis sinxela, monoxénica (a anemia falciforme) ata unha máis complexa, polixénica, como o cancro de mama; 2) a progresión no desempeño das prácticas científicas. Pártese dunha actividade na que se require elaborar un modelo "material" sobre a expresión dos xenes para explicar a anemia falciforme; continúase con dúas tarefas nas que é preciso aplicar o modelo a outras enfermidades humanas; e remátase a secuencia coa aplicación do modelo inicial elaborado para establecer as relacións evolutivas entre dúas enfermidades.

A toma de datos tivo lugar no transcurso normal das distintas sesións. A investigadora, presente en seis sesións gravadas en son e vídeo tivo un papel de observadora non participante, co propósito de non influír no desenvolvemento das sesións. Decidiuse optar por catro instrumentos para a recollida de datos e triangulación: 1) enquisas aos docentes, 2) os informes escritos das tarefas, 3) as gravacións en son e vídeo, 4) as notas de campo da investigadora.

O proceso de análise seguido consta de varias fases. Comézase pola transcrición das gravacións das conversas, sendo a unidade de análise a quenda. Diferentes episodios son identificados, nalgúns casos, e a continuación realízase a categorización. O proceso de análise ten lugar en interacción cos datos e a literatura existente, dado que entendemos que a análise non debe partir de categorías predeterminadas (Kelly e Takao, 2002), senón que deben definirse en interacción coa literatura e os propios datos. Diversas rúbricas propostas en investigacións previas son adaptadas en interacción cos datos para abordar os diferentes obxectivos de investigación.

Publicacións

Publicación 1. Learning Gene Expression Through Modelling and Argumentation. A Case Study Exploring the Connections Between the Worlds of Knowledge

A investigación sobre prácticas científicas na actualidade pon especial interese en estudar as relacións que teñen lugar entre prácticas como a modelización e a argumentación científica (e.g., Blanco-Anaya, Justi e Díaz de Bustamante, 2017; Passmore e Svoboda, 2012). Na investigación sobre aprendizaxe de bioloxía, resulta de especial interese analizar estas relacións entre prácticas en contextos como a aprendizaxe de como a xenética e evolución, onde o alumnado presenta dificultades (Kampourakis e Zogza, 2009; Shea, Duncan e Stephenson, 2015).

A modelización pode axudar aos estudantes a comprender e argumentar sobre temas relacionados coa xenética (Reinagel e Bray Speth, 2016). Neste traballo proponse modelizar a expresión dos xenes como vía para aprender xenética molecular e identificar os procesos e entidades que participan que non son visibles, así como para explicar enfermidades cunha compoñente xenética.

Este estudo está enmarcado na proposta de Tiberghien (2000) sobre os dous mundos do coñecemento, o "mundo das teorías e modelos" e o "mundo dos obxectos e eventos" que forman parte dos procesos modelización, segundo esta autora. Neste caso, amplíase o marco de Tiberghien (2000) engadíndose un terceiro mundo que se corresponde co "mundo das representacións". Preténdese examinar como interaccionan as prácticas de modelización e argumentación, así como as conexións que establecen entre os tres mundos do coñecemento na modelización da expresión dos xenes polo alumnado. Nesta publicación abórdanse as preguntas de investigación P1 e P2 da tese.

A análise do discurso permitiu identificar un repertorio de operacións de argumentación e de modelización e as conexións que establecen entre os mundos do coñecemento. A operación de modelización máis frecuente é de carácter manipulativo, sendo as relacionadas co meta-coñemento da práctica escasas neste contexto. En canto ás operacións de argumentación, o uso de probas é a predominante durante todo o proceso de modelización. Pola contra, as relacionadas coa crítica son pouco frecuentes, o que revela dificultades polo alumnado para avaliar enunciados e modelos propostos por outros. As conexións co mundo natural son as menos frecuentes, o que apunta a necesidade de prestar atención a este dominio de coñecemento na modelización.

Publicación 2: Argumentation as a tool to explain the evolutionary links between human diseases: a case study

Numerosos estudos foron propostos para promover a argumentación na aprendizaxe de ciencias, xa que, malia ser unha compoñente clave das prácticas de construción de coñecemento, a súa presenza nas aulas é escasa (Berland e Reiser, 2009). Existen estudos que abordan a argumentación no contexto de aprendizaxe de xenética e evolución, mais sempre abordando ambas disciplinas por separado. Este artigo examina a argumentación e argumentos escritos do alumnado nunha actividade que requiría establecer relacións explicativas entre a anemia falciforme e a malaria. Contexto que pon en relación a xenética e a evolución.

Nesta publicación abórdanse as preguntas de investigación P3 e P4 da tese. A análise céntrase nos argumentos escritos construídos en grupos polo alumnado participante, tanto no que se refire á súa estrutura causal, como á súa calidade en base a coñecementos aplicados e xustificacións aportadas. Ademais, analízanse os datos empregados na elaboración de argumentos finais consensuados sobre as relacións entre as dúas doenzas.

Diversas rúbricas foron adaptadas da literatura en interaccións cos datos para levar a cabo esta análise. Os resultados apuntan ás dificultades dos estudantes para construír argumentos de calidade en termos de usar unha linguaxe causal clara e nocións de xenética e evolución. A maioría do alumnado utiliza os datos proporcionados na tarefa, mais parte destes datos son reformulados para acomodarse ás súas teorías previas. Representacións sociais e culturais relacionadas coa orixe da anemia falciforme así como posicións teleolóxicas son identificadas no discurso escrito.

Publicación 3. Examining reasoning practices and epistemic actions to explore students' understanding of genetics and evolution

Este artigo céntrase na análise dos movementos discursivos e prácticas de razoamento no discurso oral do alumnado nunha tarefa, a mesma que na publicación 2, que require explicar as relacións entre a anemia falciforme e a malaria. Examínanse as interseccións entre a retórica e a argumentación, así como as accións epistémicas que mobilizan neste contexto.

Nesta publicación abórdanse as preguntas de investigación P5 e P6 da tese. A análise dos movementos retóricos e do uso de probas permite identificar tres marcos de coñecemento nos que o alumnado se sitúa á hora de discutir as relacións entre as dúas enfermidades humanas. O tipo de accións epistémicas identificadas e nas que participa o alumnado, parecen estar directamente relacionadas co contido dos datos proporcionados, resultado que apunta á importancia destes. Ademais, as accións epistémicas parecen condicionar o nivel de sofisticación das explicacións elaboradas sobre as relacións evolutivas entre dúas enfermidades humanas. Isto relaciónase coas dificultades atopadas no emprego dunha adecuada terminoloxía sobre evolución e sobre xenética no discurso oral. Identifícanse no discurso, de igual xeito que nos argumentos escritos, representacións sociais relacionadas con diferenzas culturais e biolóxicas entre grupos humanos e posicións teleolóxicas.

Discusión xeral

O uso de datos como probas é un fío condutor ao longo da tese. No primeiro artigo vemos como ten un papel fundamental, sendo a operación de uso de probas a máis frecuente e a que permite unir os tres mundos de coñecemento. O rol no segundo e terceiro artigos vén dado polo deseño da propia tarefa, que require ao alumnado analizar e usar un repertorio de datos con distinto nivel epistémico para chegar a unha conclusión final sobre as relacións entre a anemia falciforme e a malaria. Neste caso, os resultados amosan que o alumnado utiliza en cada momento os datos que se lles proporcionaban, mais en ocasións acomodan estes en base ás súas teorías previas e construcións culturais e sociais. A análise dos datos do segundo e terceiro artigo apunta á existencia de ideas alternativas sobre xenética e evolución. Parte destas ideas están relacionadas con explicacións teleolóxicas, e outra parte, con representacións sociais relacionadas coa orixe da anemia falciforme en África. A análise do discurso oral permítenos comprobar que o alumnado non foi quen de construír unha explicación sofisticada sobre a relación entre a malaria e a anemia falciforme.

Outro elemento en común que emerxe da análise dos tres artigos ten que ver coas dificultades do alumnado para moverse entre distintos niveis de organización biolóxica (moleculares, celulares e individuais), o que está en coherencia con investigacións previas (por exemplo, Marbach-Ad e Stavy, 2000; van Mil Boerwinkel e Waarlo, 2013). Na primeira tarefa, analizada no artigo 1, os materiais proporcionados no kit pretendían servir para facilitar a identificación de entidades de distintos niveis de organización biolóxica (molecular e celular). A tarefa abordada nas publicacións 2 e 3, relativa ás relacións evolutivas entre dúas enfermidades, presentaba datos destes niveis pero tamén o nivel de poboación. Os estudantes tiveron dificultades á hora de discutir en profundidade os datos de diferentes niveis presentados que poderían axudar a construír unha explicación evolutiva.

Conclusións

A análise do obxectivo 1, *examinar as interaccións entre a modelización e a argumentación e as súas conexións cos tres mundos* *do coñecemento no contexto de aprendizaxe da expresión dos xenes en alumnado de secundaria*, permítenos establecer cinco conclusións:

1. Identifícanse unha serie de operacións argumentativas e de modelización durante a modelización a expresión dos xenes por parte do alumnado no contexto de explicar unha enfermidade humana.

2. O "uso de probas" foi unha operación central no proceso de modelización da expresión dos xenes, que permitiu conectar os tres mundos do coñecemento (teorías e mundo natural; teorías e representacións; e representacións e mundo natural).

3. Examinar a modelización permite identificar as conexións entre os tres mundos do coñecemento relacionados coa expresión dos xenes que establecía alumnado. O mundo natural foi o menos frecuente na modelización da expresión dos xenes.

4. Parece que existe unha relación entre a sofisticación das representacións, as conexións entre os mundos do coñecemento e as interaccións entre argumentación e modelización. Un maior número de conexións produciuse cando se estableceron máis interaccións, o que resultou nunha representación máis sofisticada.

5. A crítica foi unha operación difícil de realizar polo alumnado mentres se dedicaban á construción do modelo, dando explicacións deterministas.

A análise do obxectivo 2, *examinar os argumentos e datos empregados polo alumnado de secundaria para explicar as relacións entre dúas enfermidades humanas na aprendizaxe de xenética e evolución*, permítenos establecer dúas conclusións:

6. Foron escasas as consideracións de xenética e evolución na maioría dos argumentos finais escritos consensuados polo alumnado sobre as relacións entre a anemia falciforme e a malaria.

7. A calidade dos argumentos escritos do alumnado cando explicaban relacións entre a anemia falciforme e a malaria foi baixa. A maioría dos grupos usaba os datos parcialmente ou reformulados nos seus argumentos.

A análise do obxectivo 3, *examinar as interseccións entre a retórica e a argumentación, e as accións epistémicas mobilizan os estudantes na comprensión de xenética e evolución en alumnado de secundaria*, permítenos establecer cinco conclusións:

8. A incorporación da retórica á análise da argumentación parece que axuda a comprender como o alumnado forma argumentos sobre xenética e evolución neste contexto particular.

9. A participación do alumnado nas prácticas epistémicas parece estar influenciada polos datos facilitados.

10. O nivel de sofisticación das explicacións sobre as relacións evolutivas entre dúas enfermidades humanas está condicionado polas accións epistémicas realizadas polos estudantes.

11. O alumnado mostrou dificultades para empregar unha adecuada terminoloxía sobre evolución e sobre xenética no discurso oral. As opinións teleolóxicas tamén foron indentificadas nas interaccións orais.

12. O alumnado mostrou dificultades para crear explicacións biolóxicas conectando entidades biolóxicas e procesos pertencentes a distintos niveis de organización biolóxica.

Implicacións educativas

Implicacións educativas relacionadas co primeiro obxectivo de investigación:

Suxerimos en futuras implementacións das tarefas, solicitar aos estudantes que indiquen de maneira explícita cando se moven entre os niveis de organización biolóxicos, co fin de que sexan capaces de conectar os niveis de organización. Para axudar ao alumnado a establecer máis relacións co mundo natural e evitar a confusión entre o fenotipo e o xenotipo, recomendamos, por unha banda proporcionar para a modelización fenotipos recoñecibles como a acondroplasia ou a polidactilia. Por outra banda, para aumentar as conexións co mundo natural suxerimos que o profesorado faga explícitos os mundos do coñecemento durante o proceso de modelización e que promocione o uso de probas neste proceso.

Xa que a modelización pode realizarse mecanicamente se non se articula a interacción entre prácticas e entre mundos do coñecemento, o profesorado debe facer explícitos repetidas veces o contexto e os obxectivos durante a modelización para que os estudantes non os perdan de vista.

Implicacións educativas relacionadas co segundo obxectivo de investigación:

Os resultados apuntan á importancia de proporcionar datos que axuden ao alumnado a identificar e reflexionar sobre os seus coñecementos previos da xenética e evolución, co fin de desenvolver coñecementos científicos axeitados a parir destes.

Traballar na clase con datos pode ser un xeito de axudar aos estudantes a comprender a evolución como un proceso continuo que está a ocorrer actualmente e está conectado á nosa vida cotiá, incluso coas enfermidades que padecemos, como a anemia falciforme e a malaria.

Implicacións educativas relacionadas co terceiro obxectivo de investigación:

Os resultados deste estudo suxiren que as accións epistémicas están relacionadas co contido da información proporcionada durante a tarefa. Desempeñan un papel na construción de explicacións sofisticadas na xenética e na aprendizaxe da evolución, dado que os procesos biolóxicos nos dous dominios implican actores diferentes que hai que considerar. Seguindo a Ferrari e Chi (1998) propoñemos que para promover a comprensión do proceso de selección natural, é importante que os estudantes poidan comprender os múltiples niveis de organización dos organismos vivos, así como as diferentes escalas temporais e espaciais nas que opera a evolución. Unha implicación educativa é a necesidade de abordar estas accións epistémicas de xeito explícito en relación cos datos facilitados nas actividades de argumentación.

ABSTRACT

This thesis aims to examine scientific and reasoning practices as well as epistemic actions while students learn genetics and evolution in the context of explaining diverse human diseases.

Recently, there has been a paradigm shift towards a conception of science education as learning through the participation in scientific practices (NRC, 2012). It has been also emphasized the importance of exploring the relationships between modelling and argumentation (Mendonça & Justi, 2013) in specific contexts, such as genetics and evolution. These authors propose that modelling in science is inherently argumentative. This thesis seeks to investigate the interactions between both practices, as well as how they help to connect the three worlds of knowledge (Tiberghien, 2000) in the process of modelling gene expression.

Arguments can be included within scientific practices, but also within reasoning practices. Within the reasoning practices, Martins, Mortimer, Osborne, Tsatsarelis & Jiménez-Aleixandre (2001) propose to explore a broader set of discursive strategies, such as rhetoric. Few studies in science education analyse students' learning from a rhetorical perspective, so little is known about the role of rhetoric in the construction of arguments and in the application of knowledge.

The objectives of this research are: O1) To examine how modelling and argumentation interact and connect the three worlds of knowledge in the context of learning gene expression; O2) To examine secondary students’ arguments and data used while developing explanatory links between two human diseases in genetics and evolution instruction and O3) To examine the intersections between rhetoric and argumentation, and epistemic actions in students’ discourse in the contest of learning genetics and evolution.

To achieve these goals, a teaching sequence about genetics and evolution was designed in collaboration with two biology teachers. The sequence includes four activities about diverse human diseases that engage students in modelling and argumentation. The participants are twenty 15-16 years-old students working in small groups.

The methodology is qualitative (Denzin & Lincoln, 2000) and draws from discourse analysis. Data collection includes audio and video recordings of all sessions, field notes and the written reports and materials elaborated by the groups.

The analysis of O1 allowed the identification of a set of argumentation and modelling operations performed by students when modelling gene expression. The examination of the interactions between both practices and their connections with the worlds of knowledge reveal that the use of evidence plays a central role in this process of modelling. Besides, the connections to the natural world were difficult to perform by students.

The examination of O2, about students' written arguments and use of data for making explanatory links between two human diseases, shows students' difficulties to build quality arguments in terms of a causal structure and the application of genetics and evolution notions.

Regarding O3, the analysis of rhetorical moves and the use of evidence uncover diverse frames of thinking when reasoning with data about two human diseases and their relationships. Furthermore, four epistemic actions were identified. Results point to their influence in the level of sophistication of explanations about the evolutionary links between two human diseases provided by the students.

We hope that this thesis helps to advance science education research on scientific practices in genetics and evolution education, given the novelty of the context and approach used. The incorporation of the lenses of rhetoric to the analysis of argumentation and the application of a framework related with the three worlds of knowledge for the analysis of modelling are potential contributions that aim to open the scope of the research in modelling and argumentation.

1. INTRODUCTION

1.1 JUSTIFICATION OF THE RESEARCH

This doctoral thesis focuses on investigating secondary students' performance of argumentation and modelling, as well as the reasoning practices and epistemic actions enacted when learning genetics and evolution. The publications included in this thesis as a compendium of articles address, on the one hand, the study of argumentation and modelling practices and their mutual interactions in relation to the worlds of knowledge that are put into play when modelling gene expression. On the other hand, they introduce rhetoric into the analysis of argumentation and examine the use of evidence and the epistemic actions performed by students in the context of learning together genetics and evolution.

The main reason for addressing this research project is related to personal and professional concerns of the researcher, a secondary school science teacher who has noticed that secondary students show difficulties for learning genetics and evolution. Another motivating factor was the need to connect both domains, evolution and genetics, using significant contexts, such as those addressed in this thesis. This concern is aligned with the existence of a large body of research regarding genetics education, which reveals students' difficulties both in understanding and in applying the model of gene expression. Moreover, in the case of evolution, the identification of teleological positions in the literature (e.g., Kampourakis & Zogza, 2009; Puig & Jiménez-Aleixandre, 2010) understanding this theory in terms of purpose or a tendency towards improvement is another reason for addressing this research.

Genetics research is progressing with new data and new techniques (Shea, Duncan & Stephenson, 2015) as well as new concepts and new terms (Brown, 2008; Flodin, 2017). Scientific advances in the field such as gene therapy, genotyping tests and the use of stem cells require decision-making and a critical literacy from citizens. Regarding evolution, according to Dobzhansky (1973) *nothing in biology makes sense except in the light of evolution*. Evolution continues to operate nowadays, something that students do not always identify (Puig, 2013). For instance, it can be associated with the presence of human diseases, being particularly clear in the case of the relationships between malaria and sickle cell disease (hereinafter SCD) addressed in this thesis. Current research into genetics and evolution education suggests that these two domains could be connected in order to improve their understanding. Previous studies point to the benefits of teaching genetics before evolution because it improves students' understanding (Mead, Hejmadi & Hurst, 2017). It has also been suggested that specific emphasis on genetics during instruction may enhance conceptual change in evolution (Kampourakis & Zogza, 2009). There is scarce evidence regarding the benefits of genetics and evolution instruction through students' engagement in scientific practices, being this one of the main contributions of the thesis.

This research also contributes to two personal objectives. On the one hand, as a teacher, it contributes to the search for innovative teaching methodologies that facilitate learning about genetics and evolution through scientific practices in the secondary school classroom. On the other hand, as a researcher, it seeks to contribute to the study of the origin and possible causes of students' learning difficulties in both domains through the analysis of scientific practices and rhetoric. The development of resources and teaching materials for the instruction of gene expression and its application to diverse contexts related to human diseases is also a goal of this thesis.

Furthermore, these motivations are connected to the science education research developed within the research group RODA (Reasoning, Discourse and Argumentation) at the University of Santiago de Compostela (USC). The investigation focuses on investigating the processes of students' participation in the scientific practices of production, evaluation and communication of knowledge in different contexts and educational levels. In the case of this thesis, secondary education is addressed since it is the educational level in which genetics and evolution are included in the curriculum (CCEOU[1], 2015). In addition, the articles of the thesis were developed within the framework of two national projects. Publications 1, 2 and 4 are related to the project "Scientific Practices in Science Teaching and Learning, Dimensions in Transference and Performance" (SCI-PRAC), code EDU2015-66643-C2-2-P. In particular, with two project objectives related to designing materials that promote argumentation, its articulation with modelling practices and with the analysis of the performance of these two practices in the science classroom.

Publication 3 has been developed within the framework of this project and it was completed in a second project that recently began in 2019, "Promoting the development of critical thinking and the social and metacognitive dimension of epistemic performances in science classrooms in the post-truth era" (ESPIGA) code PGC2018-096581-B-C22. The connection with this second project is with one objective dealing with the analysis of the cognitive domain in students' performance of epistemic practices.

The thesis draws from a previous research developed within the RODA group about the use of evidence and argumentation in learning genetics in secondary education (Puig, 2013). This study revealed the existence of deterministic positions among secondary students in relation to the model of gene expression. This thesis suggests the incorporation of modelling gene expression to improve its understanding, as well as helping to overcome deterministic positions. Modelling has been proposed as a way of understanding biological processes that are not visible (Venville & Donovan, 2008). We believe that this practice is a suitable starting context for genetics learning, given the variety of elements and processes at the cellular and molecular level that are difficult to visualise (Freidenreich, Duncan & Shea, 2001). In addition, the thesis follows Shea, Duncan & Stephenson's proposal

1 CCEOU: Regional Council of Culture, Education and University

(2015) that supports beginning the instruction with molecular genetics, using modelling as a way of learning molecular processes which are involved in gene expression, before transferring this knowledge to the construction of arguments about Mendelian genetics.

Considering the current Spanish curriculum (CCEOU, 2015), the context of genetics is used as a starting point before moving towards learning about evolution, which has shown to increase the students' understanding of evolution (Mead, Hejmadi & Hurst, 2017). To this end, it was decided that the sequence would end by addressing together evolution and genetics in order to favour students' effective learning of both domains.

Publication 4 develops and justifies the design of the teaching sequence for this thesis, which allows to formulate the research objectives of the study. This design was developed in collaboration with the biology teachers involved and the scientific content of the activities was validated by an international expert in clinical genetics. Moreover, an analysis of the literature in genetics and evolution learning was carried out.

Articles 1, 2 and 3, which addressed the objectives of the thesis, are closely linked since: 1) they all analyse scientific practices, modelling (paper 1) and argumentation; 2) they focus on the examination of the use of evidence. In the case of paper 1, attention is on the use of evidence during the process of modelling gene expression; and in the case of papers 2 and 3, the analysis focuses on the students' use of evidence when making explanatory links between two human diseases; 3) papers 2 and 3 are based on the results obtained in the previous papers. They advance in the direction of the objectives proposed in the thesis.

Publication 1 addresses the analysis of modelling and argumentation processes while students engage in modelling gene expression model to explain SCD (task 1 of the teaching sequence). The paper helps to advance in the analysis of modelling, providing a framework based on Tiberghien's (2000) proposal regarding the worlds of knowledge. Our proposal includes a third domain or world of knowledge called the world of representations. In addition, a rubric proposed by Jiménez-Aleixandre, Puig, Bravo and Crujeiras (2014) is modified in order to identify the operations of argumentation that appear in this context. The examination of the modelling and argumentation operations allows us the identification of the interactions that occur between both practices, and the connections established among the three worlds of knowledge. This article was developed in collaboration with M. P. Jiménez-Aleixandre, an international expert in argumentation in science education research.

In publication 2 the focus of analysis is on the written arguments presented by the groups when participating in a task that includes genetics and evolution contents. It is an argumentation task structured in 4 stages that involves the progressive analysis of data with a different epistemic level in order to establish connections between sickle cell disease and malaria and reach a final conclusion. On the one hand, the quality of final written arguments agreed upon in the groups is examined, and on the other hand, the use of data and its role in establishing successive arguments throughout the task is explored. The analysis reveals difficulties in the construction of arguments, both in the use of justifications and in the application of scientific terminology. In addition, teleological positions are identified. The results of this article suggest the need for oral discourse to be analysed in detail in order to better understand the processes that lead to the construction of these arguments, as well as the possible causes of the detected difficulties.

Publication 3 is based on the results obtained in paper 2 and the task under analysis is the same. Rhetoric is introduced to the analysis of oral argumentation. In particular rhetorical moves (Swales, 1990) and the use of evidence in argumentation as well as the intersections between them, are analysed. This publication also includes the analysis of epistemic actions, a framework of analysis which adapted Pontecorvo & Girardet's proposal (1993). The analysis of this paper allows the identification of frames of thinking which students are positioned in, as well as the epistemic actions performed. These results help to understand how epistemic actions related to the use of time scales and the ability to define notions can influence students when establishing complex connections in biological processes, such as the coevolution between two human diseases.

It is worth noting that the analysis in this article was initiated during a three-month pre-doctoral research stay at the University of Aberdeen, partially funded by an ESERA travel Award 2016. This gave rise to the co-authorship of the third publication with Professor Laura Colucci-Gray, who contributed to the incorporation of the framework of rhetoric in research.

In order to prepare this collection of thesis publications, it was necessary to prepare proposals prior to national and international conferences. In addition, the advances of the thesis were presented in two summer schools of recognised international prestige. Firstly in 2015, it was presented at the Sandra K. Abell Institute for Doctoral Students (SKAIDS), held at the University of Colorado Boulder (USA) between the 12th and 17th of July 2015; and secondly, at the Esera Summer school 2016, held at Ceske Budejovice (Czech Republic) between the 22nd and 26th of August 2016. Some posters were created at these summer schools and these were presented in specific poster sessions at both NARST 2016 and ESERA 2017.

The conference papers and posters developed during the thesis are displayed below.

Ageitos, N. & Puig, B. (2015). Unha proposta didáctica de modelización e argumentación científica sobre enfermidades xenéticas. Communication presented in *III Encontro Mocidade Investigadora*, Santiago de Compostela, Spain, 25th to 26th of March 2015.

Ageitos, N. & Puig, B. (2015). Construír o modelo de expresión dos xenes para explicar enfermidades xenéticas. Communication

presented in *XXVIII Congreso Enciga*, Sarria, Spain, 19th to 21st of November 2015.

Ageitos, N. & Puig, B. (2016). La modelización para el aprendizaje de enfermedades genéticas. El caso de la anemia falciforme. Poster in *V Seminario Ibero-Americano CTS, IV Seminario CTS*, Aveiro, Portugal, 4th to 6th of July 2016.

Ageitos, N. & Puig, B. (2016). Students' arguments and argumentation to explain the evolutionary links between two human diseases. Communication presented in *ERIDOB*, Karlstad (Sweeden), 5th to 9th of September 2016.

Ageitos, N. & Puig, B. (2016). Exploring the Articulation of Scientific Practices of Modeling and Argumentation in a Sequence on Genetic Diseases. Póster presented in *NARST Annual International Conference*, Baltimore, EEUU, 14th to 17th of April 2016.

Ageitos, N.; Puig, B. & Colucci, L. (2017). Comunication in the Simposio *Prácticas de argumentación en el aula y su contribución a la competencia científica*. *X Congreso Internacional sobre Investigación en la Didáctica de las Ciencias*, Sevilla, Spain, 5th to 8th of September 2017.

Puig, B. & Ageitos, N. (2017). Interactions between Modelling and Argumentation while Building the Model of Gene Expression. Communication presented in the Symposio "Deepening Students' Understanding of Modern Genetics: Four Approaches that Link Molecular Genetics with Mendelian Genetics". *NARST Annual International Conference*, San Antonio, EEUU, 22nd to 25th of April 2017.

Ageitos, N.; Colucci-Gray, L & Puig, B. (2017). Examining students' understanding of genetics through a linguistic analysis of thinking strategies. Paper presented at *ESERA Conference 2017*, Dublin, Ireland, 21st to 25th of August 2017.

Ageitos, N. & Puig, B. (2017). Interactions between argumentation and modelling in genetics' instruction about human diseases. Poster presented at *ESERA Conference 2017*, Dublin, Ireland, 21st to 25th of August 2017.

Ageitos, N.; Colucci-Gray, L & Puig, B. (2018). Students' arguments and reasoning in genetics: dealing with the complex interactions between genotype and phenotype in the expression of animal diseases. Communication presented in *XII Conference of European of Researchers in Didactics of Biology*, Zaragoza, Spain, 2nd to 6th of July 2018.

Ageitos, N. & Puig, B. (2018). Las prácticas científicas en la enseñanza sobre genética: argumentación sobre el modelo de expresión de una enfermedad animal. Communication presented in *28 Encuentros de Didáctica de las Ciencias Experimentales*. A Coruña, Spain, 5th to 7th of September 2018.

Ageitos, N.; Colucci-Gray, L & Puig, B. (2019). Arguing to explan the evolutionary links between two human diseases. A case study research. Communication presented in *13th International Conference for ESERA*, Boloña, Italia, 26th 30th August 2019.

1.2 OBJECTIVES

The main goal of this thesis is to examine the scientific and reasoning practices as well as epistemic actions performed by secondary students when learning genetics and evolution in the context of explaining human diseases. In order to address this general goal, it is necessary to explore, on the one hand, modelling and argumentation practices enacted by students and their mutual interactions in connection with the worlds of knowledge; and on the other hand, the reasoning practices and epistemic actions performed by students.

This general goal is addressed through three research objectives, and their related research questions:

O1. To examine how modelling and argumentation interact and connect the three worlds of knowledge in the context of learning gene expression. This is addressed through the following research questions, that paper 1examines:

RQ1) What argumentative and modelling operations do students enact in the process of modelling gene expression? Specifically, which operations allow connecting the three worlds of knowledge?

RQ2) What are the interactions between modelling and argumentation in modelling gene expression? To what extent do these interactions help students connect the three worlds of knowledge and modelling gene expression?

O2. To examine secondary students' arguments and the data used while developing explanatory links between two human diseases in genetics and evolution instruction. This is addressed through the following research questions, analysed in paper 2:

RQ3) What is the nature of students' arguments while explaining the evolutionary links between two human diseases?

RQ4) What data do students mobilise and how do they use them to support their arguments regarding the relationships between these two diseases?

O3. To examine the intersections between rhetoric and argumentation, and epistemic actions in students' discourse in the contest of learning genetics and evolution. This is addressed through the following research questions, analysed in paper 3:

RQ5) What frames of thinking emerge from the examination of students' rhetorical moves and use of evidence when they are learning about topics in genetics and evolution?

RQ6) What epistemic actions help students to make explanatory links between genetics and evolution?

1.3. THEORETICAL FRAMEWORK

The theoretical framework of this thesis can be situated within the epistemic education in science. Aligned with this approach, science is considered as a group of practices that have a cultural and social nature related to the community which they are developed in. This section addresses the most relevant aspects and notions of the theoretical framework. The aim is to provide a general view of the theoretical foundations of this thesis. These aspects are:

1. The Worlds of Knowledge and the Interactions between Modelling and Argumentation in Modelling Processes
2. Intersections between Rhetoric and Argumentation.
3. Learning Genetics and Evolution. Difficulties and challenges.

1.3.1 The Worlds of Knowledge and the Interactions between Modelling and Argumentation in Modelling Processes

There is a consensus in the scientific community that science learning should be promoted by students participating in the epistemic objectives of science (Kelly & Licona, 2017). Authors such as Ford (2008), support a change in science education to allow students to develop an understanding of how science works and how knowledge is built. One of the proposals which has been presented with the aim of achieving this objective, is the idea of allowing for participation in scientific practices at the centre of teaching and learning science (Jiménez-Aleixandre & Crujeiras, 2017).

This thesis focuses on students' performance in modelling and argumentation practices and in their possible interactions.

Modelling is a scientific practice which is based on explaining how or why something works the way it does, and through this practice it is possible to attain a better understanding of the natural world (Knuuttila, 2005). This practice, which is considered as one of the three scientific practices in the PISA framework (OECD 2018), consists of elaborating models which include the practice elements (construction, use, assessment and review of scientific models) as well as the meta-knowledge that guides and motivates the practice (Schwartz et al., 2009).

This thesis follows the definition of the **model** proposed by Gericke, Hagberg & Jorde (2013), who stated that a model is a simplified representation of a phenomenon produced in order to create explanations and predictions. Gilbert, Boulter and Elmer (2000) proposed the classification of models according to their ontological characteristics, differentiating between expressed and mental models. Expressed models are those which are communicated to others and which are placed in the public domain using one or more means of representation. However, mental models are considered to be more internal, personal, idiosyncratic, incomplete and unstable (Greca and Moreira, 2000). Research in psychology and cognitive science suggests that when we observe reality and we appropriate it, we are representing it, we are building our own mental model (Izquierdo, 1999).

According to Schwarz et al. (2009), meta-knowledge of models, or the knowledge of nature and the role of models, helps to make this practice meaningful for students. It is important for them to understand how and why models are used (and we add this particular type of model, the representation), as well as the limitations of these models. In this thesis, the external representations have been considered as ways of knowledge (Pérez-Echeverría & Scheuer, 2009) which focus on showing the audience visual information through painting, diagrams or tables, among others (Tufte, 1983). Among all the different types of external representations, the focus of this paper is on the material models created to explain gene expression.

Justi and Gilbert (2002) and Justi (2006) proposed a model that could explain the modelling process (models' construction) from the creation of the mental model to the expressed model. According to these authors, this process can be summarised in phases that are consecutive, but which can be repeated, and which can go in the opposite direction. According to Tiberghien (2000), the interpretation of the material world by a person or a community is a modelling activity. This research draws from this notion of modelling and modifies it. We understand that in biology, and, especially, in genetics, modelling implies the interpretation and explanation of an entity, phenomenon or process of the natural world, such as the phenotype; and that this process is mediated by the world of representations. For Tiberghien (2000), modelling involves two worlds of knowledge, the world of objects and events and the world of theories. The world of objects and events refers to those aspects that are observable and that we can perceive. Whereas the world of theories is formed by the theoretical dimension and the models that are constructed when an area of knowledge is studied.

In this thesis the framework proposed by Tiberghien (2000) has been modified in order to integrate external representations as a third knowledge domain or a world of knowledge, alongside the "theories" and "objects and events" worlds, which can be seen in figure 1.1. According to this approach, the modelling processes can be seen in terms of interactions between the three worlds of knowledge.

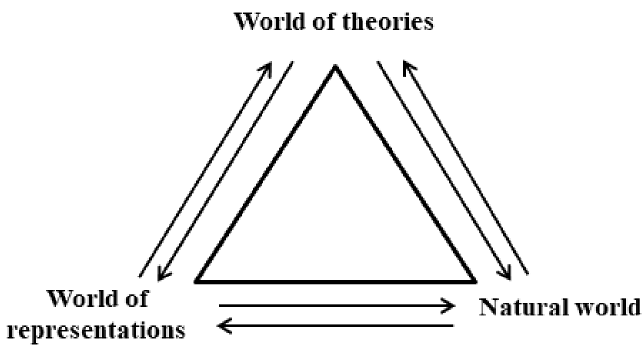

Figure 1.1: Three worlds of knowledge, adapted from Tiberghien (2000), published in Puig, Ageitos & Jiménez-Aleixandre (2017).

We suggest that student participation in model-based learning can contribute to the development of operations related to modelling and argumentation and to their interactions. We understand that the act of modelling is intrinsically argumentative given that almost all aspects of modelling, from formulating the objective to communicating the model and reviewing and assessing it, are intimately related to argumentation (Berland & Reiser, 2009; Passmore & Svoboda, 2012). In addition, we have suggested that argumentation may be responsible for the connections between the three worlds of knowledge, since it allows to make explicit the processes of change from one world to another as well as the operations performed in these processes.

Following the latest research trends that have suggested the need for the scientific argumentation and modelling practices to be analysed together (e.g., Clark, Sengupta, Brady, Martinez-Garza, & Killingsworth, et al., 2015; Passmore & Svoboda, 2012), this thesis aims to investigate the operations that take place in the performance of both practices and their possible interactions. Modelling is a process that relates the epistemic and cognitive aspects of science, such as prediction and explanation (Erduran, Kaya & Cetin, 2018). For this reason, teaching contexts based on modelling facilitate the appearance of argumentative situations that involve a single student, a group of students and their teacher (Gilbert & Justi, 2016).

Despite the increasing number of studies relating the scientific practices, it remains a poorly researched topic, as Evagorou & Puig (2017) have pointed out. This thesis deals with the study of argumentation and modelling practices and their interactions in relation to the three worlds of knowledge.

1.3.2 Intersections between Rhetoric and Argumentation

A central aim of science education is to help students make informed decisions regarding socio-scientific issues that have an impact on their lives (e.g., Dawson & Venville, 2010), as well as getting them to use their scientific understanding to question and argue critically about scientific advances. We argue that such aims are not separate but intertwined. To this regard, Martins et al. (2001) highlighted the importance of engaging students in discursive practices in science, such as rhetoric and argumentation in the construction of scientific knowledge. Their contribution signalled a shift in research into science education, moving towards the analysis of discursive interactions in the classroom over the last decades. However, although these authors advocated the role of rhetoric and argumentation in science education, nonetheless, rhetoric has not been widely explored (Osborne, 2001).

This paper is based on the idea that argumentation is a social practice in which community members try to explain the studied phenomena by assessing, criticising and revising conclusions through discourse (Berland & Reiser, 2011). Participating in argumentation is a process of "arguing to learn" and "learning to argue" (e.g., Andriessen, 2006; von Aufschnaiter, Erduran, Osborne & Simon, 2008), and to learn this requires sustained practice (Ryu & Sandoval, 2012). According to Sandoval and Morrison (2003), students should participate in epistemic discourse, what means that they should participate in discussions that involve arguing the motives and criteria they use to choose certain explanations, as well as discussing the role of evidence in their explanations. Bearing all of this in mind, argumentation can be understood as the assessment of statements through the combination of available evidence and relevant theory (Jiménez-Aleixandre & Erduran, 2008).

In this research, argumentation is also considered as a systemic practice (Erduran, Özden & Park 2015), one that involves epistemic and linguistic aspects. As indicated in Billig's seminal work (1987), argumentation is based on a system of rules, which are established based on agreed procedures, such as reliance on the burden of evidence and the use of words with established meaning.

Through argumentation, discussion may not be consensual, however, it aims to be cumulative, leading to the reinforcement of ideas and knowledge in use. Equally, we see rhetoric as a vital component of language as well as a tool for understanding scientific discourse. The term rhetoric can be used to refer to the articulation of different modes of communication, including language, images and gesture, which are used to produce coherent texts, helping to shape a given view of the world (Driver, Newton & Osborne, 2000).

Studies on language have emphasized the intersections between argumentation and rhetoric as discursive practices that might shape students' thinking or other epistemic activities (Kelly & Bazerman, 2003). In contrast with argumentation, rhetoric is more concerned with rule formation, on other words, with the questions and linguistic moves which are aimed at exploring meanings and the making of 'images' via the use of words, which may derive from different values and practices.

The intersections between rhetoric and argumentation have not been investigated in biology education. Such a gap accounts for a missing dimension in science education research, considering how cultural practices – mediated by rhetoric - interface with argumentation, what means the range of arguments which are deemed possible or valid. This thesis proposes that by recovering the rhetorical dimension in the analysis of discursive practices in science education it will be possible to provide important cues as to how students can be supported by gaining a more sophisticated understanding of biological topics.

In biology education, rhetoric is important for understanding students' thinking through argumentation due to the abstract nature of the topics involved (Pontecorvo & Girardet, 1993), and in some cases, such as evolution and genetics, due to their multifaceted and controversial nature. For instance, a previous study conducted by Sandoval and Millwood (2005) addressed the topic of evolution learning, presenting a method that assessed the warrant of explanatory claims, the sufficiency of the evidence explicitly cited to support the claims and the students' rhetorical use of inscriptions in their arguments.

Science education studies need to place emphasis on the elements that affect the nature of the arguments produced by students, not only on their adequacy. Understanding how and why arguments are produced in a particular manner is important for science educators in order to obtain a real insight into students' thinking and critical thinking skills, skills which are required in order to tackle everyday life issues related with the rapid advances in science. This thesis focuses on the students' capacity to build arguments supported by evidence, but also on their capacity to reflect on their own arguments and reformulate them based on the evaluation of data. Evaluation, referred to as how students challenge other student's arguments (Jin, Hokayem, Wang & Wei, 2016) is an important variable when constructing logical arguments (Christodoulou & Osborne, 2014).

From a socio-cultural perspective, rhetorical practices may be seen as 'linguistic devices' for the organisation and structuring of arguments. Argumentative moves can therefore be used as cues for disclosing underlying sets of rhetorical narratives, looking at how ideas of systemic interactions are visualised and addressed by students' meaning-making strategies. Emphasis is on the rhetorical or discursive moves that shape the students' arguments and construction of knowledge in genetics and evolution, two central domains of biology which are known to be difficult to teach and to learn (e.g. Bray Speth et al., 2014; Zohar & Nemet, 2002). Arguments are considered in this study as being comprised of the basic elements that Toulmin described in TAP model (Toulmin, 1958). The elements that are part of the argument structure are, according to Toulmin, the data to make qualified claims, warrants supported with backings that connect data with the claim and rebuttals.

1.3.3 Learning Genetics and Evolution. Difficulties and challenges

Difficulties related to genetics and evolution learning have been broadly reported in the literature. However, scarce research has been carried out into the context of genetics and evolution learning, primarily addressing both disciplines together. In this line, this section addresses the most common difficulties in both domains, making links between them in the final part.

1.3.3.1 Genetics learning. The model of gene expression and determinism

Over the last few decades, there have been significant conceptual and technological advances in the genetics field, many of which have reached the public domain. All of these developments have required for citizens to understand scientific ideas on genetics (Feinstein, Allen & Jenkins, 2013; Ryder, 2001). Since the goal of science education is to provide citizens with scientific knowledge, the implications of current genetic and genomic technologies on our lives must be addressed in science instruction. For this reason, molecular genetics is a central part of the secondary curriculum in different parts of the world, nonetheless it is considered to be a difficult area in science teaching and learning (Bahar, Johnstone, & Hansell, 1999).

In Spain, the official curriculum (MECD[2], 2015) introduced genetics for the first time in 4º ESO[3], within the subject of Biology and Geology, a non-compulsory subject. This means that some of the students may finish secondary school without having worked on genetics-related subjects in the science classroom.

Genetic literacy implies being able to understand, use or answer information about genetic phenomena and technologies that an individual may encounter in everyday life situations (Duncan, Rogat and Yarden, 2009). This involves being able to make informed decisions on complex socio-scientific issues (Shea, Duncan & Stephenson, 2015).

Research in this field indicates that the gap between scientific understanding of genetics and what is taught in school has increased in recent years. (Dougherty, Pleasants, Solow, Wong & Zhang, 2011). By the end of secondary school, students do not have the necessary

[2] MECD: Spanish Ministry of Education, Culture and Sports

[3] The fourth and last year of compulsory secondary education. In Spain, compulsory secondary education starts at the age of 12 and lasts four years, until students reach 16. Then, they can choose to continue with two more years of Baccalaureate (non-compulsory) until they reach the age of 18, during which they prepare for the university access examination.

understanding of genetics in order to be able to make appropriate personal and social decisions (Lewis and Wood-Robinson, 2000).

One of the difficulties highlighted in the literature regarding learning genetics is related to deterministic positions regarding the model of gene expression (e.g., Castéra, Clément, & Abrougui, 2008; Mills Shaw, Van Horne, Zhang and Boughman, 2008; Puig & Jiménez-Aleixandre, 2011). Determinism is a trend that supports the idea that "*genes invariably determine characters, so that the outcomes are just a little, or not at all, affected by changes in the environment or by the different environments in which individuals live*" (Kampourakis 2017, p. 6).

Determinists attribute social and economic differences between different human groups or genders to heredity, thus considering the differences as innate distinctions. This deterministic view often appears in the media, exclusively attributing genes the causes of human behaviour or disease (Condit et al., 1998; Nelkin & Lindee, 1995).

Keller (2005) found that belief in genetic determinism is related to negative racial stereotypes, prejudice, and sexism. For Nelkin and Lindee (2004), genetic determinism is not simply the result of a misunderstanding or simplification of science, but it may also be anchored in deep beliefs regarding social phenomena.

An earlier thesis on argumentation and the use of evidence on the model of gene expression (Puig, 2013) highlighted the difficulties for secondary school students in identifying the environmental influence on gene expression in different contexts. Likewise, Castéra and Clement (2014) demonstrated that determinism does not only appear among students, but also among teachers in several countries.

Determinism is not the only difficulty encountered when learning about genetics, given that there are others associated with the complexity of this subject, which according to Knipples (2002) are grouped into these five categories: 1) vocabulary and specific terminology; 2) mathematical content in the Mendelian genetics tasks; 3) cytological processes; 4) the abstract nature of genetics; 5) the complexity of genetics: macro- micro problems. In addition, authors such as Mills Shaw et al. (2008), refer to specific difficulties related to: a) genetic technologies; b) genetic determinism; c) inheritance patterns; d) nature of genes and genetic material; e) genetic basis of diseases; f) genetic research; g) reproductive technologies.

It is useful to be familiar with all of these difficulties in order to improve the teaching of genetics in secondary school, however Duncan and Reiser (2007) suggest that it could be classified into broader categories, such as these three: a) the invisibility and inaccessibility of genetic phenomena; b) the complexity of genetic phenomena involving several levels; and c) the ontological differences between the levels of genetic phenomena.

In order to address these difficulties, educational initiatives and proposals have emerged. The teaching sequence designed in this thesis serves as an example, taking previous contributions into consideration. Specifically, the proposal aims to improve the understanding of the model of gene expression and the connections between phenotype and genotype. Authors such as Todd and Kenyon (2015) pointed out the importance of focusing instruction on proteins, studying how they are formed, what their functions are and how they are expressed. Reinagel and Bray Speth (2016) agreed with these authors and suggest modelling as a practice to help improve the understanding of the links between genes and genotypes. Besides, Mills Shaw et al. (2008) propose tackling the first years of instruction by analysing drawings and animations of cellular and sub-cellular processes in order to improve the conceptual understanding of cellular processes and to be able to connect the different levels of organisation.

Another proposal is that of Lehrer and Schauble (2000). These authors encourage students to have the opportunity to review and construct their ideas over time in order to understand and apply concepts that do not tend to be understood until several years later.

Following this trend, the Learning Progressions (LPs) have emerged, these are hypothetical models on how the learning of a domain develops over time with adequate instruction (Duncan, Choi, Castro-Faix & Cavera, 2017). According to Todd and Romine (2017) LPs have these distinctive characteristics: they focus on some ideas and/or practices; they contain upper and lower limits; they identify different levels of achievement in terms of performance and learning; and the achievements are attained through a specific curriculum, although these are not guaranteed.

Finally, it should be noted that given that genetic determinism is a common difficulty among students that negatively affects, on the one hand, their understanding of genetics and, on the other hand, the performance of argumentation and decision-making practices; it must be addressed in the classroom. Dougherty (2009) believes that instruction in genetics should more accurately reflect what genes can and cannot do, stressing the complexity of heredity.

1.3.3.2 Evolution learning. Difficulties and proposals to address them

Evolution is one of the fundamental concepts of biology, but it is also one of the most challenging concepts to learn (Andrews et al., 2017). University biology students and pre-service teachers (Miller, Scott & Okamoto, 2006; Alberts & Labov, 2004) show alternative ideas related to evolution. In our context there is ground-breaking work that advocates the incorporation of the teaching of evolution in primary education (Vázquez-Ben & Bugallo-Rodríguez, 2018). The authors propose an intervention model for this educational stage which is based on the results obtained in a study on the challenges perceived by international experts in evolution education (Vázquez Ben & Bugallo-Rodríguez, 2017).

There are numerous studies that provide alternative ideas on the theory of evolution (Ferrari & Chi, 1998). According to Alters and Nelson (2002), these ideas can be classified according to their origin as a) ideas that arise from everyday experiences; b) ideas which are constructed by the students themselves in which they accommodate new information to their previous framework; c) ideas taught informally by other people or learned in fiction; d) vernacular ideas, that emerge from the difference between the scientific definition of a word and its everyday use; e) mistaken or religious concepts. Vernacular ideas, where metaphors are a clear example, are essential tools in science for the generation of new entities (Brown, 2008). All these alternative ideas can influence the way in which students apply molecular genetic concepts, and how they argue about the evolutionary links between two human diseases, such as malaria and SCD, which have been addressed in this thesis.

Regarding the difficulties which have emerged in this research when it comes to understanding the theory of evolution, and more specifically the mechanism of natural selection, Gregory (2009) classifies them in four concepts or thematic blocks: a) the variation that exists between individuals; b) the origin of new characters in populations; c) heredity; d) adaptation.

Explaining the origin of adaptations is a common difficulty among secondary school students, which, as Kampourakis (2013) indicates, is related to a teleological view of evolution. According to this author, teleological explanations are those in which a phenomenon is explained in terms of a final objective which it contributes to (Walsh, 2008), and which are closely related to the term "lamarckism" because they are related to Lamarck's evolution theory. In order to move beyond these teleological explanations and promote conceptual change, authors such as Kampourakis & Zogza (2009) propose replacing the old explanations with a new conceptual framework, one which is more efficient and more scientifically consistent with current theories. In this context, in addition to creating teleological explanations, students also elaborate anthropomorphic explanations and do not acknowledge the need to include causal or mechanistic reasoning when asked to articulate an explanation of biological change (Abrams & Southerland, 2001; Southerland, Abrams, Cummins & Anzelmo, 2001).

As with genetics, the complexity of the subject matter associated with random evolutionary processes can also cause problem for students (Garvin-Doxas & Klymkowsky, 2008; Mead & Scott, 2010). In many cases, students are not able to recognise random processes as responsible for biological traits (Garvin-Doxas & Klymkowsky, 2008). However, it is necessary to point out that randomness in biology is not exclusive to evolution, but these phenomena are also required in order to be able to explain genetic processes such as gene expression. Nehm & Ha (2010) have shown that students find it difficult to deal with questions about evolution between species or regarding the disappearance of characteristics in populations.

Little research has been carried out dealing with evolution and genetics learning together. One of the works that this thesis has taken as a reference is that of Kalinowski, Leonard and Andrews (2010), who have outlined the difficulties faced by university students in using concepts of molecular genetics when constructing explanations of evolution. Only a small proportion of the students (19%) made explicit reference to the molecular and genetic causes of variation in their explanations of evolution, focusing on mechanisms that operate at the level of organisms (Bray Speth, Long, Pennock & Ebert-May, 2009). This is in contrast with the idea that evolution needs concepts such as palaeontology, embryology, biogeography, molecular biology and population genetics in order to be understood (Mayr, 2002), leading therefore to a growing consensus on the need for the interdisciplinary connections in all these areas to be strengthened in order to promote student understanding and learning (Tibell & Harms, 2017).

This thesis supports the idea that placing greater emphasis on genetics during instruction can improve conceptual change in evolution (Kampourakis & Zogza, 2009). An example of this is focusing on DNA sequences during the teaching of natural selection (Kalinowski, Leonard & Andrews, 2010). Similarly, a proposal has been made to make more connections with students' prior knowledge of genetics and evolution in order to try to gain a better understanding of the mechanism of natural selection. Furthermore, following Ferrari and Chi (1998), the aim is for students to understand the multiple levels of organisation of living organisms, as well as the different temporal and spatial scales on which evolution operates.

Genetics and evolution are articulated in this thesis in the context of relating two human diseases, one of them with a genetic component.

1.4 METHODOLOGY

The thesis is framed within qualitative research which focused on the processes of knowledge construction and epistemic performances by secondary students in science classrooms. A longitudinal case study was carried out with a group of students from grade 10 (4º ESO) during the academic year 2014/2015, and grade 11 (1º Bachillerato[4]) during the academic year 2015/16. Students are from a centre in the inland of Galicia (Spain). The thesis focuses on the first year of study with the 4º ESO students.

We firstly present the methodological approach on which the thesis is situated. Secondly, the context and participants in addition to the activities developed are outlined, focusing predominantly on those which are the object of analysis in the thesis. Thirdly, the data collected, and the analysis processes are presented.

1.4.1 Methodological approach. Qualitative research

This thesis is part of qualitative research which focuses on how people build the world around them, what they do or what happens to them, in order to get a meaningful and varied perspective of the observation of the situation. According to Denzin and Lincoln (2005) qualitative research can be defined as:

> *Qualitative research is a situated activity that locates the observer in the world. It consists of a set of*

[4] The first year of non-compulsory secondary education. In Spain, compulsory secondary education lasts until students reach 16. Then, they can choose to continue with two more years of Baccalaureate (non-compulsory) until they reach the age of 18, during which they prepare for the university access examination.

> *interpretive, materials practices that make the world visible. These practices transform the world. They turn the world into a series of representations, including field notes, interviews, conversations, photographs, recordings, and memos to the self. At this level, qualitative research involves an interpretive, naturalistic approach to the world. This means that qualitative researchers study things in their natural settings, attempting to make sense of, or interpret, phenomena in terms of the meanings people bring to them.* (Denzin & Lincoln, 2005, p.3).

According to these authors, qualitative methodology aims at getting to know social reality by analysing documents or communicative acts. In the context of this study, this methodology is applied in order to analyse students' performance in scientific practices, as well as to investigate how evolution and genetics learning takes place through these practices.

Within the qualitative studies, this thesis deals with a longitudinal case study, which enables us to attain in-depth knowledge of a specific case (group of students). According to Gerring (2007), case studies can be explained using the following analogy:

> *There are two ways to learn how to build a house. One might study the construction of many houses – perhaps a large subdivision or even hundreds of thousands of houses. Or one might study the construction of a particular house. The first approach is a cross-case method. The second is a within-case or case study method.* (Gerring, 2007 p.1).

Case studies are related to social phenomena and they focus on one or more of their manifestations and on their environment (Swanborn, 2010). In addition, they have been carried out for a certain period of time and focus on detailed descriptions, interpretations and detailed explanations, as well as being based on different sources of information (reports, documents, observation notes, among others). In this thesis, the focus is on the first year of the longitudinal study, as this is the first course in which genetics and evolution appear in the curriculum. It is a unique exploratory case study (Yin, 2003) in which the performances of scientific practices are analysed by a group of twenty students in different tasks as part of a teaching sequence on genetics and evolution.

One of the most widespread criticisms of case studies is their inability to provide easily generalizable data, given that these are very specific studies (Cohen, Manion & Morrison, 2011). To improve the validity and reliability of the results obtained in the case studies, Moore, Lapan and Quartaroli (2012) suggest applying triangulation. This triangulation can be applied either by using previously tested pilot studies or by using three different sources of information. In this thesis we have used the latter by including: 1) the written reports elaborated by the students; 2) the audio and video recordings of the work sessions; 3) the researcher's field notes. Triangulation is also applied in data analysis in order to guarantee the reliability of the results obtained. The author and the supervisor of the thesis analyse the data related to the research objectives in an independent manner before contrasting the results to ensure homogeneity. In addition, a third expert intervenes by contrasting the analyses of the three objectives, therefore guaranteeing the reliability of the results.

1.4.2 Context, participants and teaching sequence

We present the context and the participants of the case study of this thesis as well as the design of the two teaching sequences in which the tasks object of study in this thesis are embedded.

1.4.2.1 Context and participants

The context in which the study has been conducted is a secondary school in inner Galicia (Spain). The school, despite being situated in a city, is semi-urban, receiving students both from the centre of the city and several neighbouring villages. Students families have a medium socio-cultural level and a large proportion of the students will continue with their secondary school studies at the end of the ESO, as can be seen in the participants of this study. The participating centre was chosen due to the interest shown by the teachers in participating in the research project.

The participants were two classes of 20 students aged between 15 and 16 years in 4º ESO and their two (T1 and T2) biology and geology teachers. The two classes were joined and the students (N=20) worked as one class. Both teachers had been working in the public education system for more than 10 years and had been teaching for several years in the same school. In the case of T1, it is worth mentioning that he had previously participated in a science education research which focused on the development of modelling in geology. Likewise, this teacher also develops his own models which he works with in the classroom.

The two teachers had met with the researchers previously in order to discuss the implementation of the tasks, the design and their adequacy, evaluating their suitability, by taking the participants' needs into account. These meetings were held both in the educational centre and in the researcher's work centre. It is important to point out that both teachers developed the tasks in the classroom, but their role was different. T1 directed the sessions and guided the different groups in the development of the activities and T2 supported T1 in the development of the activities. Both teachers met the demands of the different groups and provided each group with the necessary support.

1.4.2.2 Teaching sequence of the thesis

The activities analysed in this thesis are part of a first teaching sequence on genetics and evolution and scientific practices. The design and tasks are published in Ageitos, Puig and Calvo-Peña (2017), publication 4 of this thesis.

For the purpose of providing an overview and some context for the thesis, figure 1.2 shows the complete process for the design and implementation of the genetics and evolution learning activities project which we have worked on for two academic years (from 2014 to 2016).

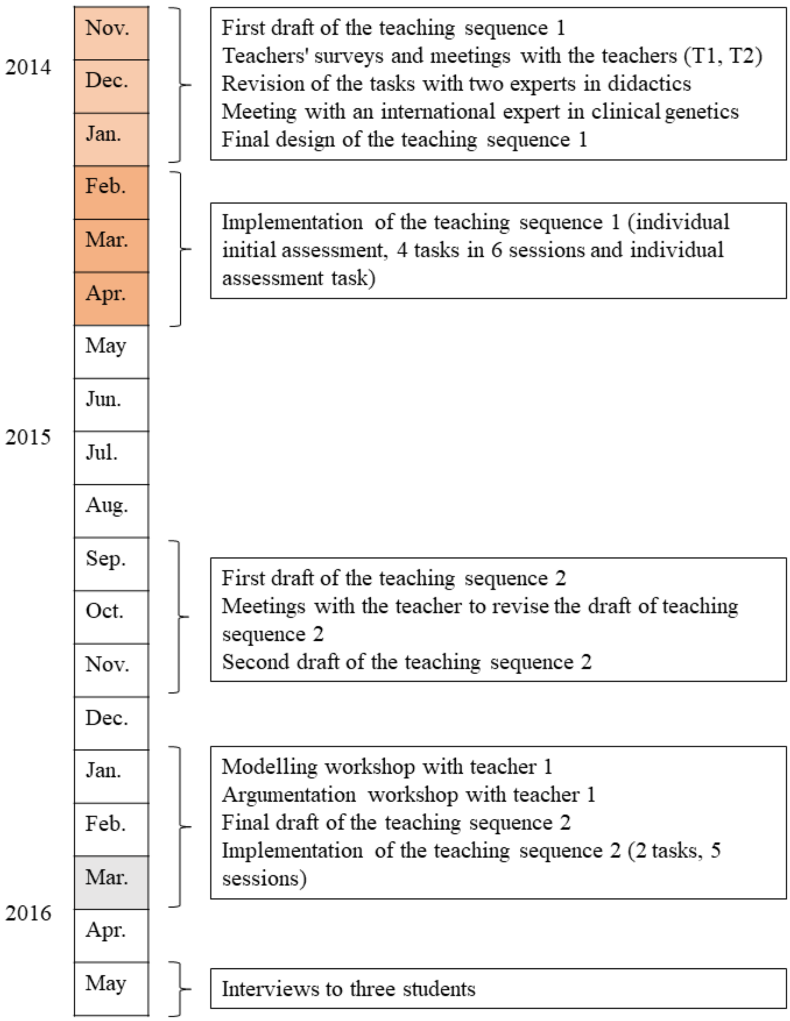

Figure 1.2 Project timing

When designing the tasks, the contents related to genetics and evolution in the current curriculum (CCEOU[5], 2015) were taking into account, as well as the results from previous research in genetics and

[5]CCEOU: Regional Council of Culture, Education and University

evolution learning. An international expert in clinical and forensic genetics advised us on the scientific appropriateness of the contents presented, as well as the suitability of the diseases and data presented to the students. In figure 1.2, the period under analysis in this thesis is highlighted in orange. The sequence entitled "Human Diseases" deals with various diseases with a genetic component that require the understanding and application of the model of gene expression. In addition, and in order to link genetics and evolution, the disease malaria is included in the last task. Malaria and SCD, illness presented in the first task of the sequence, share an evolutionarily connection that will be discussed later.

Teaching sequence 1 included four activities performed in small groups in six sessions. The activities were classified according to two criteria: 1) the level of complexity of the diseases, from a simpler, monogenetic disease (sickle cell disease) to a more complex, polygenetic one, such as breast cancer; 2) the performance progression for scientific practices. We began with an activity in which it was necessary to develop a "material" model of gene expression in order to explain SCD; we continued with two tasks in which it was necessary to apply the model to other human diseases; and we finished the sequence by applying the initial model in order to establish the evolutionary links between two diseases. Table 1.1 summarises the activities with their objectives and the scientific practices they promote.

Table 1.1 Activities of the teaching sequence

Activity	Period	Sessions	Didactic objectives	Scientific practices
Initial assessment task	February 2015	1	Express ideas regarding models in science and diseases with a genetic component	
1. Modelling gene expression to explain SCD	February 2015	2	Build a gene expression model in order to explain sickle cell disease	Modelling and argumentation
2.Sudden death, how to prevent	March 2015	2	Practice CPR techniques Create an informative	Use of evidence and modelling

it?			poster on sudden death based on scientific data Relate the gene expression model to this disease	(model transfer)
3. The Jolie effect	March 2015	1	Analyse data on breast cancer Consider different susceptible cases based on tests Make decisions to analyse genetic tests	Argumentation and use of evidence
4. Explaining the links between sickle cell disease and malaria	April 2015	1	Analyse data in order to establish evolutive links between two diseases Use tests to explain the evolutive links between malaria and sickle cell disease	Argumentation based on evidence
Final assessment task	April 2015	1	Assess the gene expression model in a new context	Modelling (model review)

The aim of the initial assessment activity, which was performed on an individual basis, was to explore the students' previous ideas and knowledge about models, human genome and diseases with a genetic component. Based on the results of this activity, the design of the activities for the teaching sequence 1 described below were revised.

Task 1. *Modelling gene expression in order to explain sickle cell disease*: This was a modelling-based task that engaged students in building a representation of gene expression in order to explain SCD. It was designed according to Mendonça and Justi's (2013) Model of Modelling Diagram (MMD) that comprises these four stages displayed in figure1.3:

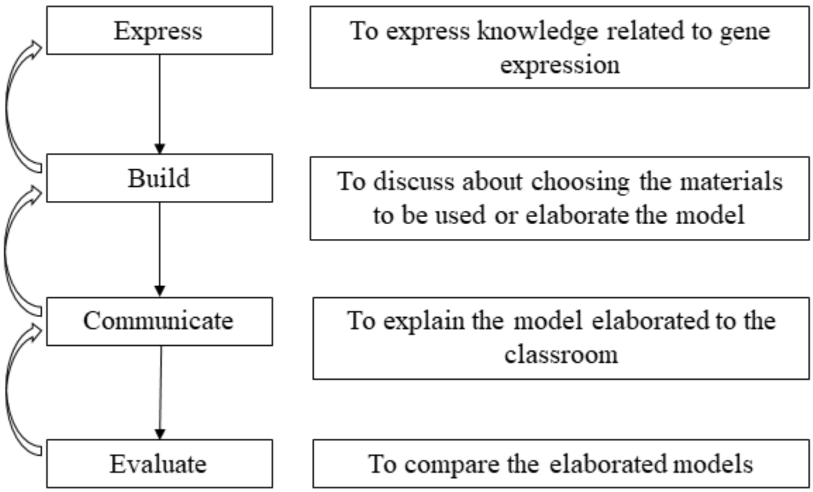

Figure 1.3: Stages of the MMD (adapted from Mendonça & Justi, 2013).

It is important to note that these four stages could overlap, repeat or alternate, it was not a linear process. The purpose was to make students reflect on the limitations of their own representations and to promote awareness of the fact that different representations can be used to represent the same phenomenon (Gericke et al., 2013).

A modelling kit was designed by the researcher and provided to students in order to help them to elaborate their own representations of gene expression. The kit contained diverse elements corresponding to the molecular entities involved in gene expression. The task required for students to understand that building a model involves selecting which entities, variables and links associated with the explained processes were to be included, and which ones were to be left out (Gericke et al., 2013). Therefore, students were instructed to select the materials that they considered necessary for this process.

The task was introduced with a piece of news about the recent inclusion of SCD in Neonatal Metabolic Screen tests in Galicia and two images of blood samples: one with sickle cell disease and another one with normal erythrocytes. Therefore, the starting point for the modelling gene expression was the phenotype and the students were required to explain SCD using their representations.

The teachers' role was to support students in the four stages of modelling when required. Both teachers scaffolded the process of identifying the elements involved in gene expression when required by students. They avoided giving direct answers to the students' questions, preferring instead to provide guidance which enabled to the students to solve them autonomously.

The task was carried out in two consecutive sessions, as shown in table 1.1.

Task 2. *Sudden death, how to prevent it?:* this activity was made up of two parts and was developed in 2 sessions. The first part consisted of the students' engagement in a cardiopulmonary resuscitation workshop led by Red Cross volunteers. The second part involved students elaborating an informative tri-fold brochure about this disease based on the data which they had previously examined. The goal was to get students to analyse the causes of the illness and revise their gene expression models and use them in this new context.

Task 3. The *Jolie effect*: this was an argumentation-based task about a complex disease, breast cancer. The task was developed in one session in which students were required to firstly read a news story about the case of Angelina Jolie (https://www.abc.es/salud/noticias/20140919/abci-cancer-mama-efecto-jolie-201409191658.html). This piece of news was selected because it is an international media case which the students were familiar with. Jolie decided to have a preventive double mastectomy after being identified as the carrier of the BRCA1 gene which is known to increase the risk of developing breast and ovarian cancers. Secondly, students had to evaluate different hypothetical cases as if they were working in a Genotyping Centre. They had to give advice to patients after having assessed both their medical and family records as to whether or not they should have the BRCA1 test. At the end of the session they had to reflect on these cases and write down the advantages and disadvantages of genotype tests.

Task 4. *Explaining the links between sickle cell disease and malaria*: in this case two human diseases, SCD and malaria, were compared by analysing the different data provided.

Following Kalinowski et al. (2010), this task was designed to help students to construct explanatory frameworks and make explicit connections between concepts in the context of molecular genetics and evolution. Students had to apply previously used knowledge, for example on mendelian and molecular genetics and evolution to describe the links between two human diseases, malaria and SCD.

The reasons for selecting SCD and malaria were as follows: a) among the scientific community their evolutionary relationship is well known given that malaria parasites and humans coevolved providing an adaptive advantage to the SCD heterozygotes; b) these are topics that can be used to address the widespread difficulties reported in the educational research literature concerning the understanding of and relationship between these illnesses (Jarrett, Williams, Horn, Radford & Wyss, 2016); and c) they are relevant to the students, as SCD was recently included in the Neonatal Metabolic Screen in Galicia (Spain).

The task was introduced by means of a short discussion with the students. The driving question was presented as follows: "Is there any connection between SCD and malaria?" To try and answer the question, students were provided with a) four numbered envelopes with information and b) a piece of cardboard to arrange the information and write down their conclusions. The structure of the task is shown in Figure 1.4.

Information provided in step 1

Conclusions:

Information provided in step 2

Conclusions:

Information provided in step 3

Conclusions:

Information provided in step 4

Final conclusions:

Figure 1.4 Structure of the task “Explaining the links between sickle cell disease and malaria”.

The task was designed to encourage students to use evidence to justify their claims by giving them different data in a structured manner.

Students were instructed to open one envelope at a time in numerical order and discuss the information provided, in order, before writing down their conclusions. This step was repeated four times, each time with a different envelope. The structure of this activity aimed to help students to revise all previous conclusions in the light of new evidence.

The information was divided into four sets with information arranged in chronological order, including different types of information related to malaria and SCD, including historical, diagrammatic and genetic information. The information provided has been summarized in table 1.2, alongside the knowledge of genetics and evolution that was required, and a brief description of the epistemic strategies which were needed to solve them. The reason for using a chronological order was to recreate the process followed by scientists, by using the evidence available in order to build a hypothesis and modify it as new evidence emerges. The information was presented both in textual and visual form, as scientific meaning is derived from both modalities of representation (Lemke, 1992, 1998). Students completed the task in one 50-minute session.

Table 1.2 Information provided in the task (Ageitos, Puig & Colucci-Gray, in press).

Envelope	Type of data	Information provided	Genetics/ evolution knowledge	Epistemic strategies
1	Historical	First register of a case of SCD	Molecular genetics	Interpreting historical data about SCD and identifying the shape of the erythrocytes affected by the disease
	Historical	First visualization of the shape of a sickle cell erythrocyte		
	Historical	Cases reported in early XX century		
	Visual	Image of blood sample with sickle cell erythrocytes		
2	Genetic	Description of the phenotype of a family affected by SCD	Mendelian genetics	Completing the family tree of a hypothetical family by interpreting phenotype information using

	Visual	Family tree to complete		Mendelian genetics nomenclature
	Visual	Photograph of the members of the family		
3	Visual	Electrophoresis of heterozygous and homozygous individuals with SCD	Mendelian and molecular genetics and biochemistry	Identifying: a) the differences between homozygous and heterozygous individuals suffering from SCD, b) the relation between the genotype of SCD and the amount of malaria parasites
	Visual	Amount of malaria parasite in individuals with/without SCD		
	Aetiology	Description of malaria		
4	Historical	Haemoglobin mutation caused by SCD	Evolution and Mendelian and molecular genetics	Relating the mutation in the haemoglobin of red blood cells to the red blood cell affected by SCD; identifying the distribution area of malaria and SCD
	Historical	DNA sequence mutation identified that causes SCD		
	Visual	Maps of distribution of SCD and malaria		

Teaching sequence 1 ended with a final evaluation activity that was done in the classroom, but without the presence of the researchers. This final activity, entitled "Tracking sickle cell anaemia", consisted of two questions. The first presented a case of a girl who has sickle cell disease who wanted to travel to areas where there is a high risk of contracting malaria. The second question asked students to use their material models to explain the girl's illness to her, and for this they were given a colour photograph of their models.

Teaching sequence 2, which was developed in the second period (academic year 2015-2016) is related to teaching sequence 1 and was designed considering the difficulties encountered in this first unit. The tasks are summarised in table 1.3. Since this sequence is not analysed in the thesis, the activities of this sequence are not discussed in detail.

Table 1.3. Activities in teaching sequence 2

Activities	**What were the causes of the deaths of Martiño's pigs?**	**The mosquitoes of Albufera. Can the mosquito population change when faced with an insecticide?**
Period	March 2016	March 2016
Sessions	2 sessions	3 sessions
Didactic objectives	Apply the model of gene expression to argue about the causes of an animal disease. Evaluate data related to the possible causes of an animal disease. Use available tests to evaluate a deterministic model of gene expression in this context.	Evaluate statements related to evolution. Develop a model evolution to explain the Albufera phenomenon. Graphically represent changes in a population over several generations. Relate the developed model to an evolutionary perspective. Revise the teleological arguments based on the model of evolution which has been elaborated.
Scientific practices	Argumentation	Modelling and argumentation

1.4.3 Data collection

The data collection took place during the regular course of the different sessions. The researcher, who attended six sessions, played the role of a non-participating observer in order to ensure that they did not influence the development of the sessions. Four instruments were chosen for data collection and triangulation: 1) teachers' surveys, 2) written task reports, 3) audio and video recordings, 4) the researcher's field notes.

1. *Surveys*: Before the implementation of the tasks, a survey of six open-ended questions was conducted for the teachers involved. The survey was aimed at getting to know their experience and knowledge of scientific practices, in particular regarding modelling. The main purpose was to identify their vision regarding this work methodology. Also, given that a teacher had previous experience in research about modelling, the survey aimed to find out how he assessed the introduction of models and modelling in science teaching in his classes.

2. *Written reports:* These included the written materials produced both individually and collectively in the two analysed tasks, which were: the representations of the gene expression models and the written explanations from each group (Task 1); the written reports where they placed the data provided in Task 4 and the partial and final conclusions drawn.

3. Audio and video recordings: The purpose of these recordings was to record the participants' discourse and their interactions among themselves and with the teacher while performing their tasks. A total of five sessions were recorded. Before the beginning of each session, the researcher and a collaborator from the research group set up a video recorder and an audio recorder to ensure that everything that happened in each group would be recorded. The video images are necessary in order to conduct a multimodal analysis and identify each member of the group when they are speaking. It is also necessary to check which elements they were handling during modelling and when elaborating arguments from data. The literal transcription of the interactions in the groups and with the teacher is produced for subsequent analysis.

4. Field notes. The researcher was in charge of collecting field notes for each of the sessions. These notes included the distribution of tables and groups in the classroom, comments on the progress made in different tasks, incidents, schemes and drawings made by teachers on the blackboard, as well as difficulties observed during the development of the activities.

1.4.3.4 Data analysis

This section presents the main analysis strategy adopted in this thesis, the discursive analysis, as well as the process which was followed in order to address the objectives and research questions.

1.4.3.4.1 Discourse analysis

As Ibáñez García (2014) points out, philosophical study traditionally focused on the inner and private world, but with the so-called linguistic turn, the work began to focus on the study of linguistic statements. Therefore, we move from considering language as a means for expressing ideas to its role as an instrument for constructing them. Over the last decades, discourse analysis has become a theoretical perspective related to learning in social environments, the definition of which we have taken from Gee and Handford (2012):

> *Discourse analysis is the study of language in use. It is the study of the meanings we give language and the actions we carry out when we use language in specifics contexts.* (Gee & Handford, p.1).

According to Gee and Handford (2012), discourse analysis can be approached in two different ways, one based on linguistic analysis (content analysis and grammar) and the *critical* approach, which aims to provide a description beyond language functioning, social problems and controversies present in society and, therefore, in discourse. This thesis combines both approaches, as it incorporates rhetoric into the analysis of argumentation on socio-scientific issues.

Bearing in mind that teaching is a social activity, language is therefore important for understanding how learning takes place in a classroom situation (Lemke, 1990). For example, in the science classroom teachers play the role of information conveyors that students must subsequently understand and communicate, sometimes through oral language (Jiménez-Aleixandre & Díaz de Bustamante, 2003). People involved in science teaching and learning, therefore, "speak science," as Lemke (1997) indicated. This implies not only learning the language of science, but also its values. According to Gee (2005), discourse can be an identity tool shared by members of a community. In this sense, classroom discourse can provide knowledge about the students' understanding of certain topics, but it can also provide information about values, beliefs, or ideologies.

In the last decade, discourse analysis has evolved towards the so-called multimodal discourse analysis (hereinafter MDA). It is considered that social actors perform different actions although, they are not exclusively discursive (Norris, 2004). MDA extends the study of language by combining it with images, scientific symbology, actions, music, sound or gestures (O´Halloran, 2013). For this reason, in this thesis we chose this method of analysis, since in the science classrooms, specifically in the one studied in this thesis, students not only discuss science verbally, but also construct models (representations) to explain natural processes that will be analysed together with oral and written language.

In summary, studies that use discourse analysis allow us to know how the knowledge constructed by students is moulded, and at the same time, it is moulded by discourse and social practices.

1.4.3.4.2 Data analysis process

Data analysis was performed following the series of steps summarised in Figure 1.5.

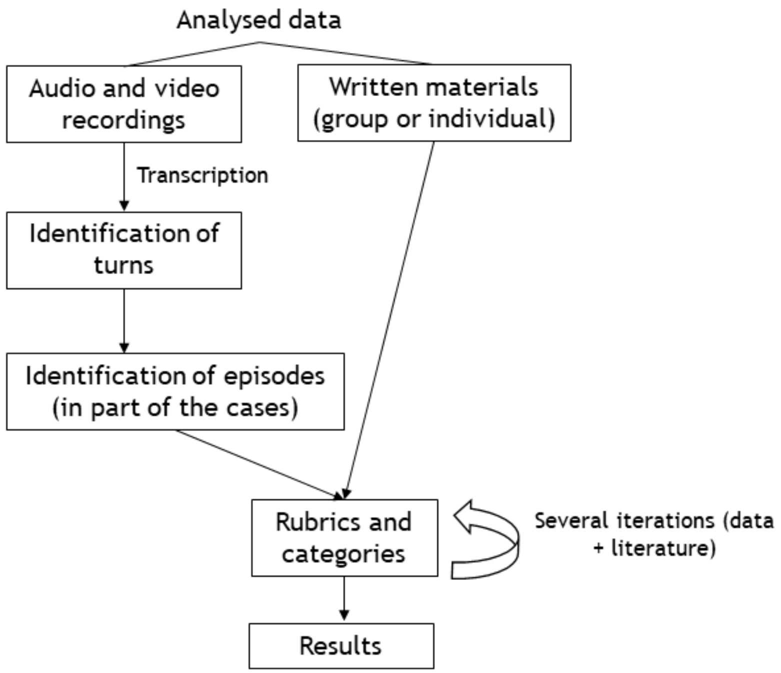

Figure 1.5 Data analysis process.

First of all, the audio data was transcribed in order to analyse the speech and be able to study the meaning of the language used (Gee, 2005). Since transcription is a change of medium, this leads to a change in the data (Gibbs, 2012). The transcription is done as literally as possible, respecting the terminology used and also the language (Galician, Spanish).

From the transcription, the unit of analysis is the turn of speech, this means that each intervention by the participants in the conversation, or a fragment of said turn if different statements or operations are reflected in it. After a first reading, turns can be compiled into episodes, the latter being made up of several turns related to the same discussed issue or the same performed action (Gee, 2005). In consecutive readings, categories are assigned to oral interventions and actions, trying to highlight the aspects which are to be analysed. In some cases, the focus will be on modelling and argumentation operations, as well as their interactions. In other cases, it will focus on discursive moves and rhetorical strategies, but it will depend on the research question which is to be answered. Table 1.4 summarises the analytical tools used for each objective, as well as the tasks that are analysed.

Table 1.4 Objects and analysis tools used in each activity to address the research objectives

Research objective	Object of analysis	Analysis tool	Sequence task
O1. To examine how modelling and argumentation interact and connect the three worlds of knowledge in the context of learning gene expression	Modelling and argumentation processes. Interactions between both. Relationships between the worlds of knowledge in modelling.	Argumentation operations (building upon Jiménez-Aleixandre et al 2014) and modelling operations (adapted from Schwartz, 2009) Worlds of Knowledge (adapted from Tiberghien, 2000).	Modelling gene expression to explain sickle cell disease

To examine secondary students' arguments and the data used while developing explanatory links between two human diseases in genetics and evolution instruction.	Quality of written arguments (causal language and application of genetic notions)	Causal structure of arguments (Ryu & Sandoval, 2012); Genetics and evolution considerations (adapted from Zohar & Nemet, 2002)	Explaining the links between sickle cell disease
O3. To examine the intersections between rhetoric and argumentation, and epistemic actions in students' discourse in the contest of learning genetics and evolution	Argumentation (use of tests) and rhetoric in oral discourse. Epistemic actions in discourse	Rhetorical moves (Swales, 1990). Frames of thinking (Pontecorvo & Girardet, 1993). Epistemic actions (adapted from Pontecorvo & Girardet, 1993)	Explaining the links between sickle cell disease

The analytical process took place in interaction with data and existing literature, since we understand that analysis should not start from predetermined categories (Kelly & Takao, 2002), but should instead be defined in interaction with literature and the data itself. It consisted of a process of analysis that involved several cycles of reading the transcripts and reviewing the categories. These categories were elaborated from rubrics collected in the literature (see table 1.4), before being adapted to our data. The final refinement of the categories was negotiated between the various researchers involved.

The rubrics for analysing both the responses to the written documents and the models were produced in a similar way, i.e. in interaction with the data itself and taking the literature into account.

1.3.4 Ethical considerations

Since the research design involves analysing the data obtained directly from secondary classrooms and working with students and teachers, a number of ethical considerations were taken into account to ensure the integrity and dignity of the participants (McMillan & Schumacher, 2014):

- Written consent. All study participants were informed of the objectives of this study and were asked to participate in order to ensure voluntary participation. First of all, permission was requested from the centre's management team. Afterwards, the families were then given a written consent form, providing information on the purpose of this research and the use of the data, and their authorisation was requested for the participation of the students, who were all minors. This consent allowed for the participants to be recorded both on audio and video, and it also allowed for the elaborated materials to be collected. These materials will be used, guaranteeing anonymity, therefore the images used in works derived from this research paper will always be edited to prevent the identification of participants.

- Anonymity and confidentiality. In the study presented, all participants were identified with pseudonyms in order to protect their identity. The five groups of students were identified from letter A to E, and every member of each group were given a name that begins with that letter, respecting the sex of the student. Teachers also received a pseudonym. In order to prevent the centre being identified, references to the centre and the context were limited in order to guarantee privacy. This research followed the principle of not harming or endangering participants.

2. PUBLICATIONS

2.1 PUBLICATION 1. LEARNING GENE EXPRESSION THROUGH MODELLING AND ARGUMENTATION. A CASE STUDY EXPLORING THE CONNECTIONS BETWEEN THE WORLDS OF KNOWLEDGE

In this paper, published in *Science & Education*, the focus is on the examination of argumentation and modelling practices and the connections between the three worlds of knowledge put into play by students when modelling gene expression.

Puig, B., Ageitos, N. & Jiménez-Aleixandre, M. P. (2017). Learning Gene Expression Through Modelling and Argumentation. A Case Study Exploring the Connections Between the Worlds of Knowledge. *Science & Education*, 26(10), 1193-1222. https://doi.org/10.1007/s11191-017-9943-x.

https://doi.org/10.1007/s11191-017-9943-x

2.2 PUBLICATION 2. ARGUMENTATION AS A TOOL TO EXPLAIN THE EVOLUTIONARY LINKS BETWEEN HUMAN DISEASES: A CASE STUDY

In this paper, published in *Journal of Biological Education,* the focus is on students' written arguments and use of data in a task that requires to explain the links between SCD and malaria.

Ageitos, N. & Puig, B. (2019). Argumentation as a tool to explain the evolutionary links between human diseases: a case study. *Journal of Biological Education*.
https://doi.org/10.1080/00219266.2019.1667409.

2.3 Publication 3. Examining reasoning practices and epistemic actions to explore students' understanding of genetics and evolution

In this paper, published *Science & Education*, the lenses of rhetoric are introduced to the analysis of argumentation. Epistemic actions performed by students are also addressed.

Ageitos, N., Puig, B. & Colucci-Gray, L. (in press). Examining reasoning practices and epistemic actions to explore students' understanding of genetics and evolution. *Science & Education*. DOI: 10.1007/s11191-019-00086-6

https://doi.org/10.1007/s11191-019-00086-6

2.4 Publication 4. Trabajar genética y enfermedades en secundaria integrando la modelización y argumentación científica

This publication presents the design of the teaching sequence in which the activities analysed in this thesis are embedded.

Ageitos, N.; Puig, B. y Calvo-Peña, X. (2017). Trabajar genética y enfermedades en secundaria integrando la modelización y argumentación científica. Revista Eureka sobre Enseñanza y Divulgación de las Ciencias, 14 (1), 86-97. DOI: https://doi.org/10.25267/Rev_Eureka_ensen_divulg_cienc.2017.v14.i1.07.

http://hdl.handle.net/10498/18848

3. DISCUSSION

In this chapter the results of the thesis' research objectives are discussed. These results are firstly dealt with individually in relation to the questions related to each objective, and they are then discussed in a general manner, connecting the findings of this thesis.

3.1 Discussion of the Results Related to each Objective

3.1.1 Modelling and argumentation and their connections to the three worlds of knowledge

The first research objective, *To examine how modelling and argumentation interact and connect the three worlds of knowledge in the context of learning gene expression,* is specified in these two research questions in Paper 1.

RQ1) What argumentative and modelling operations do students enact in the process of modelling gene expression? Specifically, which operations allow connecting the three worlds of knowledge?

RQ2) What are the interactions between modelling and argumentation in modelling gene expression? To what extent do these interactions help students connect the three worlds of knowledge and modelling gene expression?

By analysing the "Modelling gene expression in order to explain sickle cell disease" activity, we are able to explore argumentation and modelling practices and their mutual interactions, as well as the connections among the three worlds of knowledge.

The examination of RQ1 led to the identification of a repertory of argumentation and modelling operations as well as the connections established between the three worlds of knowledge.

Considering that the task engaged students in building a representation to explain gene expression, modelling operations were more frequent than argumentative ones. Operations related to the meta-knowledge of modelling (Schwarz et al., 2009), were the least common operations. The task design may have affected this, given that a kit was provided, meaning therefore that students paid more attention to manipulative operations such as “Building the model” than to others. Students spent time selecting and placing the elements provided in the kit to build their representations. This part of the modelling process in which students selected and moved elements from the kit around, glued them or transcribed and translated the sequences corresponded to “doing the lesson” (Jiménez-Aleixandre, Bugallo-Rodríguez and Duschl, 2000). Considering that this was the first modelling-based task in the teaching sequence performed by students this was not an unexpected result. Students may have needed get used to these kinds of modelling-based activities and this may partially explain why participants focused on building the model in the physical way.

Regarding the argumentation operations, the use of evidence played a central role, appearing throughout the modelling process. It is the only operation which connects the three worlds of knowledge. This operation includes two subcategories called “Identifying and interpreting data as evidence” and “Using evidence to support a claim: identifying and interpreting evidence”. Students engaged in these subcategories when they identified data from the three worlds of knowledge as being evidence of gene expression and included them in their representations. Another operation related to use of evidence is “Asking for evidence, data and/or justifications” and it also appears in connecting the three worlds of knowledge, but in a lower frequency than use of evidence.

The operation of critiquing did not appear frequently when modelling gene expression. This operation involves students questioning certain elements provided in the kit as part of gene expression. The fact that students included the elements in their final representations, despite not being sure about their participation in gene expression, is an indication of their difficulties in engaging in critique. Furthermore, few students made counterclaims, this means that they did not usually propose an alternative idea to the one that was criticised.

Regarding the connections among the three worlds of knowledge, connections between the world of theories and the world of representations were more frequent than the connections with the natural world. Students retrieved their knowledge about the elements and processes involved in gene expression to build their representations, which could explain why they established more connections between the world of theories and the world of representations than with the natural world. Moreover, references and connections to the natural world were the scarcest, and, as expected, when students linked it to the world of theories no modelling operations appeared.

The examination of RQ2 demonstrated that a relationship exists between the connections established among the three worlds of knowledge and the interactions performed between argumentation and modelling practices. A highest frequency of interactions led to more connections among the three worlds of knowledge. On top of this, this seemed to also affect the elaboration of a more sophisticated representation of gene expression.

3.1.2 Students' arguments and data used while making links between two human diseases

The second research objective, *To examine secondary students' arguments and the data used while developing explanatory links between two human diseases in genetics and evolution instruction*, is articulated in these two research questions addressed in Paper 2.

RQ3) What is the nature of students' arguments while explaining the evolutionary links between two human diseases?

RQ4) What data do students mobilise and how do they use them to support their arguments regarding the relationships between these two diseases?

The examination of these two research questions focuses on the arguments produced in a task that required students to link two human diseases, SCD and malaria. Particular attention has been placed on the students' written final arguments (in the case of RQ3) and on the written statements provided by the groups in each step of the task (in the case of RQ4).

The analysis of RQ3 allows us to identify the quality of arguments in terms of empirical and theoretical criteria. The results showed that the students' final written arguments did not include genetics and evolution concepts. One group mentioned the word "evolve" in the third written conclusion but failed to do so in the final argument. They explained that Africans have evolved variants to protect against malaria, but no further information or processes were included.

Most of the groups (four out of five groups) were not able to include genetics and evolution concepts in their final written consensual arguments. They focused more on describing some of the data provided instead of developing a final conclusion regarding the links between SCD and malaria. One group was able to use genetics notions as mutation. However, they seemed to have a teleological view regarding the role of mutation in the relationship between both diseases.

Students struggled to draw up quality written arguments using clear causal language and building strong justifications. Likewise, the students' explanations seemed to pose naïve ideas about genetics and evolution such as teleological considerations. Teleological explanations, which involve attributing evolutionary change to need, are not rare in students' discourse (Alters & Nelson, 2002; Zohar & Ginossar, 1998). For instance, students in this study considered that the relationship between the two human diseases is based on the fact that SCD is a protection against malaria. Moreover, one group explicitly attributed to humans, the need for the mutation to appear in order for a protection against malaria to be created. This result is consistent with the one proposed by group 1, who, despite acknowledging that a mutation can be positive, explicitly stated that “black people” can control this mutation based on their own will, therefore revealing teleological positions.

The analysis related to the use of data is relevant to this task as it was designed following a structure in which students were provided with data in diverse steps to help them to progressively analyze the data. Their intention was to help students to reach a final conclusion, building on all of the data provided and revising their own arguments in the process. However, when analyzing how they select and modify the data provided, students in our study struggled to integrate this data into their explanations. This analysis helps uncover cultural and social representations. Students identify the origin of SCD in Africa and link the disease to “African-Americans” or “black people”. This issue has already been reported (Jarrett et al., 2016) even though many African-Americans have never even resided in Africa (Biggs et al., 2002). The fact that students identify the idea that this group could only marry among their ethnic group demonstrates that this group has been identified as being marked by cultural differences to other groups at that time. The social representation of identifying all black people not just as Africans, but also as African-Americans appeared in the students’ arguments as in previous studies on argumentation in genetics learning (Puig and Jiménez-Aleixandre, 2011). This points to the influence of cultural knowledge when students try to make sense of the data.

3.1.3 Examination of rhetoric, argumentation and epistemic actions

To address the third research objective, *To examine the intersections between rhetoric and argumentation, and epistemic actions in students’ discourse in the contest of learning genetics and evolution*, two research questions were proposed in Paper 3.

RQ5) What frames of thinking emerge from the examination of students' rhetorical moves and use of evidence when they are learning about topics in genetics and evolution?

RQ6) What epistemic actions help students to make explanatory links between genetics and evolution?

The analysis of the oral discussion during the activity *Explaining the links between sickle cell disease and malaria* allowed us to explore the use of evidence and the rhetorical moves. This analysis helped us to uncover students' frames of thinking and the epistemic actions performed by the students. Three central frames were identified. Frame 1, *Identifying the origins of sickle cell disease in the African community*, which showed students' explanation of the origin of SCD as being in Africa. This claim appeared repeatedly in subsequent frames, demonstrating how students accommodate new data to fit into their own views. Frame 2, *identifying the pattern of inheritance of SCD,* in which students identified the pattern of inheritance of SCD, as a dominant-recessive pattern, following a discussion on sex-linked inheritance. Besides, they discussed the molecular relationship between SCD and malaria, making connections to the previous frame by recalling the origin of SCD. In frame 3, *Making evolutionary links between SCD and malaria*, students agreed that there is an evolutionary link between the two diseases. However, the link consists of a relationship between the mutation that causes SCD and the protection that it provides against malaria.

The identification of these three frames of thinking allowed us to see the perspective from which students argued and analysed the provided data in the context of linking two human diseases.

It seems that using more rhetorical moves helped participants to mobilize more data, although not necessarily demonstrating high levels of using evidence. The highest levels of use of evidence were strongly related to the enthymemes, although they did not seem to help students to achieve a more sophisticated idea about the processes being studied.

In accordance with Tibell & Harms (2017), students struggled to build interconnected biological explanations, in particular they struggled to connect biological entities and processes from different levels; between molecular genetics and mendelian genetics or genetics and evolution. This finding points to the need for both engaging students in learning genetics and evolution together and for developing teaching units to help deal with these difficulties (Kampourakis & Zogza, 2009).

The examination of RQ6 helped us identify the epistemic actions that appeared in students' discourse. Regarding the analysis of the epistemic actions, *Interpreting actions, phenomena and intentions of actors* was the one that appeared most frequently in the students' discourse. The authors expected this result given that biological processes involve different actors that need to be considered in order to be understood. The epistemic action of *Locating events and phenomena in time* appears very frequently in the first frame, as it coincides with the moment in which the historical data is provided to the students.

The epistemic actions of *Terminological and conceptual definitions* and *Locating events and phenomena in time* are absent in frame 3. This difference, in comparison with the previous frames, may be crucial in understanding why students are not able to build a complex evolutionary explanation at the end of the task. They did not seem to be able to propose the mechanisms that may be involved in the relationship that they agree exists between both diseases.

3.2 General Discussion

The analysis of data and the use of evidence is a guiding means throughout this thesis. In the first article we saw the fundamental role it plays, with the use of the evidence operation being the most frequent and the one that allows for the three worlds of knowledge to be connected. The role in paper 2 and paper 3 was given by the task design itself, which required students to analyse and use a series of data or information at different epistemic levels in order to reach a final conclusion about the relationship between SCD and malaria. In this case, the results showed that the students always used the data provided, but that they sometimes adjusted this data based on their previous ideas influenced by social and cultural constructions. In addition, the use of data as evidence for elaborating arguments about the relationships between the two diseases allows, together with rhetoric, for frames of knowledge and epistemic actions that operate in this context to be identified.

In the case of paper 2, the analysis of the data used by the students in their written arguments suggested the existence of naïve ideas regarding genetics and evolution. Some of these naive ideas were related to teleological explanations, and some to social representations related to the origin of SCD in Africa. In order to explore this in depth, the oral discourse of a group in which discursive interactions were frequent was analysed. The analysis of rhetoric, in particular of rhetorical moves, was introduced into the study of argumentation. This allowed for the frames of thinking related to the ways of reasoning about genetics and evolution to be identified.

This analysis of oral discourse allowed us to verify the appearance of teleological explanations among students, as well as the influence of cultural learning on the interpretation of historical data. One such example was their understanding that African-Americans could only marry other African-Americans and the idea of SCD being a contagious disease that was spread in Africa by an African-American slave before being passed on through inheritance within the African-American community, also appeared in the students' discourse.

We also found that students were not able to verbally construct a more sophisticated explanation of the relationship between malaria and sickle cell disease. The absence of epistemic actions such as *Locating events and phenomena in time* and *Designating terminological and conceptual definitions* could affect the fact that this group was not able to elaborate a sophisticated explanation in which the coevolution of both diseases would be beneficial for humans.

Another common issue that emerged from the analysis presented in the three papers was related to the students' difficulties in moving among the different levels of organization (molecular, cellular and individual) as was also reported in previous research (e.g. Marbach-Ad and Stavy, 2000; van Mil, Boerwinkel & Waarlo, 2013). Following Knippels' (2002) instructional model for genetics, so-called "yo-yo learning", our tasks were designed to enable students to move up and down through different organizational levels of biology. In the first task, which has been analysed in paper 1, the materials provided in the kit were related to the molecular and cellular levels, and the affecting disease on an individual level. The task addressed in papers 2 and 3, regarding the evolutionary links between both diseases, presented data from these levels but also from the population level. Students struggled to discuss, in depth, the molecular data presented that could have helped them to build an evolutionary explanation. They also struggled to link the phenotype with the protein function outcome in the first task, and this is consistent with previous studies about modelling in genetics (Reinagel and Bray Speth, 2016). Another difficulty they faced was in linking the phenotype with their representations. This could be related to the "macro–micro" problem, which also requires understanding phenomena at multiple levels of organization.

4. CONCLUSIONS AND EDUCATIONAL IMPLICATIONS

In this section we summarise the conclusions drawn from each research question. We then go on to discuss the educational implications that can be drawn from the study and its limitations. Finally, potential future lines of research related to this thesis are presented.

4.1 CONCLUSIONS

Conclusions are presented in relation to the three objectives (4.1.1, 4.1.2 & 4.1.3) of the thesis.

4.1.1 Modelling and argumentation and their connections to the three worlds of knowledge

The examination of O1. *To examine how modelling and argumentation interact and connect the three worlds of knowledge in the context of learning gene expression*, allows us to establish five conclusions:

Conclusion 1. A range of argumentation and modelling operations were identified while the students modelled gene expression in the context of explaining a human disease. The meta-knowledge operations of modelling were scarce.

The analysis of students' discourse during the modelling-based task has enabled us to identify a set of modelling and argumentation operations. The identification of modelling operations adds a deeper understanding of the elements that appear in the practice of modelling (constructing, using, evaluating, and revising scientific models), to Schwarz et al.'s framework (2009), this includes the meta-knowledge that guide this practice. The identification of argumentation operations builds on the proposal made by Jiménez-Aleixandre, Puig, Bravo &

Crujeiras (2014) related to diverse argumentative contexts. The operations related with the meta-knowledge of modelling are scarce in this context in comparison with others that are physical or manipulative ones.

Conclusion 2. The "Use of evidence" was a central operation in the process of modelling gene expression. This operation allowed for the three worlds of knowledge (theories and natural world; theories and representations; and representations and natural world) to be connected.

The use of evidence was the most common argumentation operation that appeared in the students' discourse and it favoured the connection of the three worlds of knowledge. Students identified data from the three worlds of knowledge as evidence of gene expression and included this in their representations.

The fact that students engaged in the process of building the model for a long period facilitated the frequent use of evidence. For students, the role of the data provided was crucial for building the model, this was shown when they used or asked for evidence to link their representations to their knowledge or to nature. As in previous studies regarding modelling and argumentation (Mendonça & Justi, 2013), our results demonstrate that argumentative situations appear to be related to sense making and generating explanations in the process of modelling.

Conclusion 3. The examination of modelling helped to identify students' references and connections among the three worlds of knowledge related with gene expression. The natural world was the least frequent in modelling gene expression.

The examination of students' discourse while modelling gene expression allowed us to reformulate Tiberghien's (2000) proposal of the worlds of knowledge and the references and connections among them. Besides, there were scarce connections to the natural world. This could be related to the fact that students hardly ever mentioned the disease being modelled (SCD) or the affected cells (the erythrocytes). These results confirmed the reported difficulties regarding the students' capacity to distinguish the phenotype from the genotype (Lewis & Kattmann, 2004).

Despite the fact that modelling could be considered as a way of overcoming these difficulties (Reinagel and Bray Speth, 2016), our results show that this practice helped to connect the three worlds of knowledge, although the connections with the natural world need further support.

Conclusion 4. There seemed to be a relationship between the sophistication of representations, the connections between the worlds of knowledge and the interactions between argumentation and modelling. A higher number of connections occurred when more interactions were established, therefore resulting in a more sophisticated representation.

The connections between modelling and argumentation are not new in science education research. Clement (1989) suggested that they appeared during the model-evaluation stage. Furthermore, recent studies have indicated that both practices were deeply connected, both in the construction and in the evaluation of knowledge (Mendonça & Justi, 2013). Our analysis suggests that there was a mutual contribution between both practices as previous studies on modelling and argumentation have proposed (Blanco Anaya, 2015; Mendonça & Justi, 2013). Blanco Anaya, Justi and Díaz de Bustamante (2017) indicated that the better use of models involves an improvement in the argumentative process. Our results reveal that both practices seem to continuously interact, and it is therefore difficult to establish whether argumentation promotes modelling or vice versa.

A remarkable finding is that these interactions between modelling and argumentation seemed to promote the connections among the three worlds of knowledge. This means that through the engagement in both practices, students were able to make connections between theory and practice.

By making a comparison between two groups, one of which builds a sophisticated representation, and another which builds a low complex representation, we were able to conclude that more interactions between argumentation and modelling operations enable more connections to be established among the worlds of knowledge by participants.

Conclusion 5. Critiquing was a difficult operation for students to perform while engaging in the construction of a model of gene expression.

We consider argumentation as both the construction and critiquing of statements (Ford, 2012), however, our results indicate that critiquing is challenging, as has been reported in previous studies (González-Howard & McNeill, 2017). A relevant issue is that operations related to critique, such as "critiquing" and "opposing a claim" were scarce. This indicates the low performance of this type of social interaction as well as the difficulties faced by students in evaluating other students' claims during the modelling process.

4.1.2 Students' arguments and data used while making links between two human diseases

The examination of *O2. To examine secondary students' arguments and the data used while developing explanatory links between two human diseases in genetics and evolution instruction*, leads to these conclusions:

Conclusion 6. Genetics and evolution considerations were scarce in most students' final written consensual arguments about the links between SCD and malaria.

Students struggled to use the appropriate terminology related to genetics in their final written consensual arguments, as previous research on genetics learning showed (Knippels, 2002). In this study, students also experienced difficulties regarding evolution. Instead of using notions such as "evolution" or "adaptation", participants used the word "protection" during the oral discourse when explaining the appearance of the mutation of haemoglobin to help those suffering from malaria.

Conclusion 7. The quality of students' written arguments in explaining the relationships between SCD and malaria was low. Data provided was partially used or reformulated in their arguments by most of the groups.

The examination of the quality of written arguments showed that most of the groups used an implicit causal language. This means that they were able to relate both diseases implicitly in their final consensual arguments. Regarding their justifications, most of the groups struggled to justify their claims (three out five groups). Only one group was able to use the data as evidence to justify their claims by explaining the protection that SCD provides against malaria.

Regarding the use of data provided, most of the data was partially used or reformulated in order to fit in with their previous ideas in all of the steps of the task, in particular regarding the distribution of both diseases. Students identified malaria as being only in Africa, despite being shown maps indicating its prevalence in other areas outside of Africa (specifically, Asia and Europe). In the same way they identified the origin of SCD as being in Africa, particularly among the 'African-American' community,

4.1.3 Examination of rhetoric, argumentation and epistemic actions

The analysis of O3. *To examine the intersections between rhetoric and argumentation, and epistemic actions in students' discourse in the contest of learning genetics and evolution*, allow us to formulate these conclusions:

Conclusion 8. The incorporation of the lenses of rhetoric to the analysis of argumentation seemed to enrich the understanding of the formation of arguments on genetics and evolution in this context.

The analysis of rhetorical moves indicated that students mobilized several sources of information, however the discursive moves did not necessarily support high levels of use of evidence. The highest levels tended to be related to the formation of enthymemes, although students did not seem to achieve a more sophisticated idea about the processes which were being studied. Regarding the rhetorical moves, the most frequent were enthymemes and syllogisms. In contrast, rhetorical questions and appeals to examples were scarce in the students' discourse. Enthymemes seemed to help students progress in their discussions.

Conclusion 9. Students' performance of epistemic actions seemed to be directly related with the data provided.

Four epistemic actions, that are considered as the explanation procedure used for the interpretation of particular events (Pontecorvo & Girardet, 1993), were identified in the students' discourse in a task that required for the relationship between two human diseases to be determined. The analysis pointed to the influence of the data provided in the students' performance of a specific epistemic action. In other words, the content of the information provided affected the appearance or absence of epistemic actions, what may be relevant in order to develop a better understanding regarding the relationships between both diseases. For instance, *Locating events and phenomena in time* was present very frequently in the first frame in which the information was related to the socio-historical context of the first diagnosed cases of SCD.

Conclusion 10. The level of sophistication of the explanations about the evolutionary links between two human diseases was conditioned by the epistemic actions performed by students.

Some epistemic actions were absent in part of the three frames of thinking. For instance, *Terminological and conceptual definitions* was absent in the first and the third frame. Another epistemic action, *Locating events and phenomena in time* was also absent in the third frame. The fact that the students focused on the actors involved in the discussed processes and their concern with identifying the location of both diseases, may have distracted students from the need to pay attention to the longer-term mechanisms that may be involved. The enactment of these two epistemic actions may have played a crucial role in developing a complex understanding of the evolutionary process that explains the co-existence of malaria and SCD in certain areas.

Conclusion 11. Students showed difficulties to use adequate terminology on evolution and genetics in their oral discourse. Teleological views were also identified in oral interactions.

When establishing the relationship between SCD and malaria, students did not use accurate scientific terminology. The students' oral discourse seemed to show teleological views regarding the relationship between both diseases, attributing the appearance of SCD as a protection against malaria. The results that point to this conclusion can be found by examining objective 2 and likewise they are related to the aforementioned conclusion 6.

Moreover, some of the students showed cultural and social representations in their oral discourse by identifying Africa as the origin of SCD and identifying all black people not just Africans, but also as African-Americans. African-Americans appear to be clearly identified by the students as 'actors', a group of people distinguishable from other groups due to cultural *and* biological differences. Previous studies (Biggs et al. 2002) have linked SCD to "African people" or "black people", despite the fact that many African-Americans did not live in Africa. This points to the influence of cultural knowledge, social representations and epistemic beliefs when students make sense of the data.

Conclusion 12. Students had difficulties building interconnected biological explanations which connected biological entities and processes belonging to different levels of biological organization.

Students were not able to move between the biological levels of organization presented in the task (molecular, cellular, individual and population levels) in order to build a scientific explanation regarding the relationships between both diseases. This finding is in line with Tibell & Harms (2017) suggestion that students struggle to build interconnected biological explanations. In this particular context, they struggled to connect biological entities and processes belonging to molecular genetics and Mendelian genetics as well as genetics and evolution.

4.2 EDUCATIONAL IMPLICATIONS

The educational implications that may be drawn from the conclusions are described in the following paragraphs.

From conclusions 1, 2, 3, 4 & 5, which are related to the first research objective, the educational implications are:

Modelling tasks based on MDM is revealed to be of use to teachers when designing and guiding modelling instruction, and to students when engaging in different operations during the modelling process (Puig, Ageitos & Jiménez-Aleixandre, 2017). The communication stage seems to help students to engage in revising their models, therefore favouring their enrichment. Providing a kit for modelling gene expression seems to be useful for identifying and locating cellular entities and molecular processes (transcription, translation) that are neither visible nor easy to connect. This shows the benefits of engaging students in the elaboration of a material model of gene expression. However, the results show that students still struggle with relating the genotype and the phenotype and with making interconnections among biological levels. In future implementations we would recommend for students to be asked to give explicit explanations as to how they move between the levels of organization during the process of modelling.

Modelling tasks offer students opportunities to build and evaluate explanations of the natural world (Mendonça and Justi, 2013), however, as this study shows, this process requires scaffolding. Modelling must present a clear goal for students beyond just "doing the lesson" (Jiménez-Aleixandre et al., 2000). These activities may be performed mechanically if the interaction between practices and between the worlds of knowledge is not articulated. Teachers must repeatedly make the context and objectives explicit during modelling to ensure that students do not lose sight of them. In other words, teachers must use ‘modelling talk’ in an explicit manner.

This study shows that students struggle to make connections with the natural world that corresponds to SCD. The phenotype of this disease is microscopic, and this might not help students to recognize it and connect their representations with the natural world. An educational implication is the need to provide recognizable phenotypes, such as achondroplasia or polydactyly, which can be modelled in order to help students make connections to the natural world. Moreover, diseases with a clear environmental influence, such as phenylketonuria could be modelled as a way of helping students to incorporate environmental factors involved in gene expression. Furthermore, we suggest making the worlds of knowledge explicit during the modelling process so that students are able to relate the representation to the theory and apply knowledge to build and explain the representation.

The study reveals that the "Use of evidence" operation helps connect the three worlds of knowledge, allowing the scarce connections with the natural world. This points to the central role of this operation. We believe that promoting this operation could increase the connections to the natural world and could therefore be beneficial for the students' understanding of gene expression. Teachers' training on how to promote and scaffold the use of evidence in modelling-based tasks requires further attention and research into modelling-based learning.

We also suggest the importance of guiding students in the meta-knowledge of modelling in a way that makes the modelling practice meaningful for them (Schwarz et al., 2009). For instance, by asking them to reflect on the criteria used for making modelling decisions, such as selecting and including elements in their representations; or by guiding students in the comparison of their representations in a way that will help them to understand that models can take different forms.

The operation of critiquing is scarcely performed by students in the context of building a model of gene expression. This indicates the importance of paying attention to the promotion of critiquing in the construction and evaluation of models. Social interactions oriented towards this epistemic goal should be promoted in the science classroom.

Therefore, it is important to make explicit the fact that although the activity requires for a representation of gene expression to be built according to modern genetics, there is not just one correct scientific model to relate to in the world of theories. Multiple historical models of gene function exist as Gericke and Hagberg (2007) emphasized.

From conclusions 6 & 7 which are related to the second research objective the educational implications are:

Regarding genetics and evolution instruction, as Kampourakis and Zogza (2009) stated, we consider that evolution must be learned alongside genetics, engaging students in dialogic discourses and providing experiences in which they are given the chance to discuss explanations and evaluate evidence. Moreover, this type of instruction should cover social representations and cultural learning as this study shows that these topics may affect the construction and evaluation of arguments in light of the data. Likewise, we agree with some authors' suggestions that students' alternative ideas such as teleological and anthromorphogenic explanations could be considered as a starting point for evolution instruction (Zohar & Ginossar, 1998).

Our findings also suggest that there is a need for the teaching and learning of genetics and evolution to be supported through the provision of data that helps students to use their previous knowledge as a way of helping them to build accurate scientific knowledge. Working in the classroom with data may be a way of helping students to understand evolution as a continuous process that is occurring at present and that is connected to our everyday life and even to the diseases that we suffer, such as SCD and malaria. However, this method presents some challenges to both teachers and students. More emphasis must be placed on the students' understanding of complex notions such as genetics and evolution in biology education research.

We propose developing teaching units which are designed to address these difficulties and engage students in dialogic discourses, providing experiences in which they are given a chance to discuss explanations and evaluate evidence.

We believe the aforementioned is an important responsibility for biology educators who are preparing students to be active participants in the social, cultural and ecological practices of science.

From conclusion 8, 9, 10 & 11 which are related to the third research objective the educational implications are:

The analysis of reasoning practices suggests that awareness of rhetorical discourses should be developed further by teachers in order to help students understand how they view biological processes in wider scenarios. To achieve this goal, it will be necessary to provide teachers with instruction on this matter, in addition to further professional development. We believe that by helping teachers to acknowledge the importance of 'framing', which is related to the ways in which frames are connected to particular terms (Flodin, 2017) and the manner in which said terms are connected to cultural beliefs as this would help students to become familiar with the use of frames in their discourse. Following the rhetorical perspective, the metaphorical terms which are commonly used in biology (Affifi, 2017; van Dijk, 2016) should be examined explicitly in the classroom and should be decontextualized in order to be able to examine the figurative meanings and help students understand both the biological implications and the metaknowledge behind rhetoric.

The findings of this study suggest that epistemic actions are related to the nature of the information provided. These actions play a role in the construction of sophisticated explanations in genetics and evolution learning, given that the biological processes in both domains involve different actors that need to be considered in relation with each other. Tasks designed to mobilize time-related data and/or concepts that need to be defined may enhance the use of the epistemic actions of *Locating events and phenomena in time* and *Designating terminological and conceptual definitions*. These epistemic actions are important in order to understand evolution and natural selection. In line with the ideas of Ferrari and Chi (1998) we propose that in order to promote an understanding of the natural selection process, it is important for students to grasp the multiple levels of organization of living organisms, as well as the different temporal and spatial scales in which evolution operates. The importance of time and space scales has previously been reported for developing the students' understanding of historical events (Pontecorvo & Girardet 1993), but not for considering evolution and genetics learning together. An educational implication is the need to address these epistemic actions explicitly in relation to the data provided in argumentation activities.

4.3 LIMITATIONS AND FUTURE LINES OF RESEARCH

The limitations of this study correspond mainly to its methodological design. Case studies are designed in order to allow for a deep analysis of the reality (Cohen, Manion & Morrison, 2011), therefore this would enable us to get a better understanding of a group of secondary students learning genetics and evolution's engagement in scientific practices. The drawbacks of the case studies which cannot be controlled before the study is implemented (Yin, 2003) relate to the fact that results are specific to the context, therefore avoiding the generalization of the findings. Besides, by carrying out the study in a real classroom, this means that certain elements cannot be fully controlled. Tasks were designed in collaboration with the teachers, however, the content of the lessons about genetics and evolution that took place prior to the implementation of these units were not recorded or controlled. Aspects such as the dynamics of the groups and the students' prior knowledge or motivation may affect the development of the units. Moreover, the students participating in the study changed slightly between the first and second unit, as a new school year resulted in new students joining the school and other students leaving it.

Another aspect that limits the implementation and development of the study was related to the amount of time which was available for engaging in the tasks. The Spanish curriculum is extensive and engaging in scientific-based activities requires time and sustained practice, as does the teachers' training on its instruction. A better performance could be attained if there was more time to engage in the tasks and to become more familiar with this scientific-based approach. Furthermore, students were not directly instructed on the meta-knowledge and epistemic criteria regarding the use of evidence and argumentation. Ryu and Sandoval (2012) propose not only explicit learning about the topic but also the epistemic criteria for scientific arguments in order to improve the quality of students' arguments.

We propose three future lines of research in relation to the findings and the limitations of our study:

The first research line is related to analysing epistemic beliefs. Baytelman et al. (in press) have demonstrated that epistemic beliefs and prior knowledge regarding controversial socio-scientific issues determine the different types of arguments that students construct (social, economic, ethical, scientific and ecological). In this line, the examination of how the students' epistemic beliefs might affect their ability to include different perspectives such as genetics or evolution *could help identify resources to promote students learnin*g.

The second line of research is related to a deeper analysis of the metaknowledge of modelling. As the results have shown, difficulties in engaging in the critiquing operation indicate the need to address this operation explicitly in order to promote a less manipulative understanding of modelling processes than the one addressed in the thesis.

A third line of research relates to the analysis of emotions in the students' explanations and arguments. The tasks presented in this thesis dealt with diverse human diseases. When designing these activities, the emotional component that could accompany them was not considered. However, this emotional component might influence how students perform argumentation and understand the disease, as well as the way in which the teacher presents the tasks or how the students behave around the topic. We suggest that the analysis of emotions is a dimension that can influence the construction of explanations, providing a greater understanding as to how to benefit from emotions in the classroom to promote students learning. In line with the analysis of emotions in the classroom, an adaptation of the AIR model (Barzilai

& Chinn, 2017) that takes into considerations emotions and values could be developed in further research.

We hope that the results of this thesis contribute to improving the understanding of scientific practices such as modelling and argumentation. We aim to broaden the current understanding of the role of argumentation and modelling in fostering the students' understanding of genetics and evolution, placing particular emphasis on human diseases. We also expect to shed light on the role of rhetoric in students' discourse, in particular when engaging in a task which is designed to use data as evidence to build scientific arguments. Finally, we hope that this project will help the community of teachers that are interested in knowing both how to introduce argumentation and modelling practices and how to guide these activities effectively when teaching genetics and evolution in relation to human diseases in their biology classrooms.

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